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THE GUTHRIE LECTURE.

The Origin of Spectra.

By Prof. J. C. McLennan, *F.R.S., University of Toronto.*

Delivered March 22nd, 1918.

Since Bohr * presented his views in 1913 on the origin of radiation involving the conception of a nucleus atom with permanent and temporary, stationary or non-radiating electronic orbits within it there have probably been no advances made experimentally in the field of radiation which have been more stimulating or more far reaching in their consequences than the early experiments of Frank and Hertz.† In these experiments they showed that when heated mercury vapour was traversed by electrons possessing kinetic energy acquired in passing through a fall of potential of about 4·9 volts, the vapour was stimulated to the emission of the single wave length $\lambda=2536{\cdot}72$ Å.U. This result constituted a new and, in so far as range of spectrum involved is concerned, most interesting application of the quantum theory, for it will be seen that with the relation $Ve=h\nu$, where $h=6{\cdot}6\times10^{-27}$ erg. sec., 4·9 volts is the potential fall which corresponds to the frequency of the wave length $\lambda=2536{\cdot}72$ Å.U. Interest was added to this discovery when Frank and Hertz also pointed out that they were led by their experiments to the view that when mercury vapour was bombarded by electrons the minimum energy required to ionise a mercury atom was that acquired by an electron in a field of 4·9 volts difference of potential. It was soon seen that these two results were not compatible with the theory of Bohr of the origin of radiation, for assuming the validity of the quantum theory, it is impossible for an atom which possesses a series of stationary orbits to be ionised, and, being ionised, to be capable of emitting a radiation consisting of a single wave length. Apart from this consideration, however, Frank and Hertz's experiments were interesting and stimulating in that they directed attention to certain fundamental series in the spectra of the elements and indicated the possibility of connecting up quantitatively certain numerical relationships associated with

* Bohr, "Phil Mag.," July, Sept. and Nov., 1913; March, 1914; Feb. and Sept., 1915.

† Frank and Hertz, "Verh." d. Deutsch. Phys. Ges., Vol. X., p. 457.; and Vol. XI., p. 512.

these series with the dimensions and other features of the stationary electronic orbits of the atoms themselves. These remarkable experiments of Frank and Hertz have formed the starting point of a rather elaborate piece of experimental work, in which it has been my privilege in collaboration with my students to take a part. In the communication which is to follow it will be my endeavour to outline the main features of the development which has taken place in the interval, and to indicate, if possible, the significance and trend of the investigation to date.

(1.) *Origin of Radiation and the Quantum Relation.*

Following the original experiments of Frank and Hertz and extending them to include vapours other than mercury, we have been able to show that when the vapours of mercury, zinc, cadmium and magnesium * were bombarded by streams of electrons of moderate intensity from an incandescent limed cathode, as the mean kinetic energy of the electron was increased a point was reached when the respective vapours emitted a radiation of but a single and definite wave length. With mercury this wave length was $\lambda=2536{\cdot}72$ Å.U., with zinc it was $\lambda=3075{\cdot}99$ Å.U., with cadmium $\lambda=3260{\cdot}17$ Å.U., and with magnesium $\lambda=2852{\cdot}22$ Å.U. Moreover, the impact voltages which were found to be requisite for the stimulation of these monochromatic radiations were those which are given by the quantum relation $Ve=h\nu$, ν being the frequency of the radiation emitted.

In these experiments it was also found that no additional radiation was emitted by the vapours as the electrons were speeded up until arcs were struck, which they were when the impact voltages applied were those given by the quantum relation $Ve=h\nu$ for the frequency $\nu=(1{\cdot}5, S)$. This frequency it will be noted, was the frequency of the shortest wave length of the series represented by $\nu=(1{\cdot}5, S)-(m, P)$ in the spectrum of each of the vapours mentioned above.

This work has since been extended by Bergen Davis and Goucher,† who have shown, when using mercury vapour of low density, bombarded by electrons, that while a radiation of wave length $\lambda=2536{\cdot}72$ Å.U. was emitted *without ionisation*

* McLennan and Henderson, "Proc." Roy. Soc. A, Vol. XCI., p. 485 McLennan, "Proc." Roy. Soc. A., Vol. XCII., p. 307; McLennan, "Phys. Rev.," Vol. X., p. 84, July, 1917.

† Bergen Davis and Goucher, "Phys. Rev.," Vol. X., No. 2, p. 101, 1917.

when a mean impact voltage of 4·9 volts (the quantum relation voltage) was used, an additional radiation of wave length λ=1849 Å.U. appeared when the mean applied impact voltage was 6·7 volts. For this radiation it will be seen the quantum relation $Ve=h\nu$ again applied. They also showed that ionisation by impact without an apparent increase in radiation occurred with an impact voltage of about 10·4 volts. This voltage, it will again be noted, corresponds by the quantum relation to the frequency of the shortest wave length of the principal series $\nu=(1{\cdot}5, S)-(m, P)$.

It follows, therefore, that the arcing potential with mercury vapour under bombardment by streams of electrons of moderate intensity is the same as the ionisation potential for mercury atoms, and that both these magnitudes are given by the quantum relation using the frequency $\nu=(1{\cdot}5, S)$. This result, therefore, confirms the view originally put forward by me,* which was also put forward independently by Bohr about the same time in so far as the relation of the ionisation potential to the spectral frequency $\nu=(1{\cdot}5, S)$ is concerned.

The results obtained by Bergen Davis and Goucher, who used the photo-electric effect for the detection and identification of the radiations emitted, have recently been extended to the vapours of zinc and cadmium by Mr. Ireton † and myself, using the photographic method. With zinc vapour it has been found that by the use of quantum impact voltages it is possible to stimulate the radiations of wave length λ=3075·99 Å.U. and λ=2139·33 Å.U., and with cadmium vapour the radiations of wave length λ=3260·17 Å.U. and λ=2288·79 Å.U. In the case of both vapours no indication of the existence of the shorter wave length was obtained on the plates until the impact voltage demanded by the quantum relation for it was applied. With impact voltages applied higher than those corresponding to the above mentioned shorter wave lengths no additional radiation was obtained until arcs were struck. In so far, then, as our own experiments and those of Bergen Davis and Goucher go it is clear that they seem to indicate that by the use of "quantum" determined impact voltages it is possible to make the vapours of mercury, zinc and cadmium emit radiation consisting of one, and only one, wave length, and that by the use of still

* McLennan and Henderson, "Proc." Roy. Soc. A., Vol. XCI., p. 490, 1915.

† McLennan and Ireton. Communicated to the "Phil. Mag.," Oct., 1918.

higher "quantum" impact voltages to make the vapours emit a radiation consisting of two, and only two, wave lengths. Fig. 1, which is typical of all the vapours referred to, shows the results obtained with zinc. Reproduction No. 1 shows the many lined spectrum of the zinc spark. Reproduction No. 2 shows the line at λ=3075·99 Å.U., which was brought out when an impact voltage of 5·6 volts was used, and reproduction No. 3 shows both the lines corresponding to λ=3075·99 and λ=2139·33 Å.U., and was obtained with an impact voltage of 7·5 volts. As 5·8 volts is the quantum voltage for λ=2139·33 Å.U. and 4 volts that for λ=3075·99 Å.U., it will be seen that when an applied P.D. of 5·6 volts was used we were well above that demanded for the longer wave length, and just below that required by the quantum theory to bring

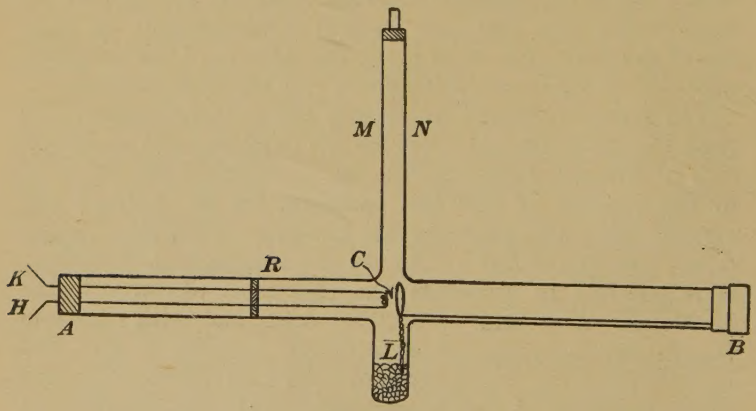

FIG. 2.

out the shorter wave length. It is interesting to record that even with exposures of 10 hours' duration no indication was obtained on the photographic plates of the wave length 2139·33 Å.U., when an impact voltage of 5·6 volts was used. The form of the fused quartz tube used in carrying out these experiments is shown in Fig. 2, and has been fully described elsewhere. *C* was an incandescent tungsten cathode, and *L* was the zinc metal which was vaporised. It should also be stated that in measuring the impact voltage allowance was made for the drop in potential over the incandescent filament and its leads.

TABLE 1.

Series Spectra.

$(1{\cdot}5, S)-(m, p_2)$ series.

Mercury.	Zinc.	Cadmium.	m.
2536·72	3075·99	3260·17	2
1435·59	1632·08	1710·58	3
1307·83	1468·90	1537·89	4
1259 31	1408·86	1474·06	5
1235·91	1379·38	1442·60	6
1222·44	1362·59	1424·40	7
1213·97	—	—	8
—	—	—	—
—	—	—	—
Lt 1188·00	1320·00	1378·7	∞

$(1{\cdot}5, S)-(m, P)$ series.

Mercury.	Zinc.	Cadmium.	m.
1849·6	2139·33	2288·79	2
1402·71	1589·64	1669·3	3
1268·9	1457·64	1526·73	4
1250·6	1376·97	1469·35	5
—	—	—	—
Lt 1188·0	1320·0	1378·7	∞

From Table I. it will be noted that the wave lengths $\lambda=2536{\cdot}72$ Å.U., $\lambda=3075{\cdot}99$ Å.U., and $\lambda=3260{\cdot}17$ Å.U. are respectively the first members of the combination series $\nu=(1{\cdot}5, S)-(m, p_2)$ and the wave lengths $\lambda=1849{\cdot}6$ Å.U., $\lambda=2139{\cdot}33$ Å.U., and $\lambda=2288{\cdot}79$ Å.U., the first members of the singlet principal series $\nu=(1{\cdot}5, S)-(m, P)$. The other members of both these series for the three metals, as the table shows, are all beyond the range of wave lengths which can be recorded by a spectrograph with an optical train of quartz. It would be interesting to extend the experiments described above so as to see if the higher members of these two series would come out on the plate one by one if the impact voltage of the electrons were increased to that given by the quantum relation for their frequencies. To do this it would be necessary to use a fluorite spectrograph or a vacuum grating spectrograph for the range intermediate between $\lambda=1900$ Å.U. and $\lambda=1400$ Å.U., and a vacuum grating spectrograph for the range below $\lambda=1400$ Å.U.

To work in this direction some experiments were set on foot for me by Mr. Ainslie with a fluorite spectrograph and others by Mr. Lang with a vacuum grating spectrograph. It was found that with both instruments much time was consumed in working out technical details. The results obtained to date with them will be published shortly, and they will show that with the fluorite spectrograph it is now easy to obtain

spectrograms down to λ=1400 Å.U. With the vacuum grating spectrograph spectrograms well below λ=600 Å.U., can be readily obtained. Through time devoted to war work, however, the experiments had to be discontinued before it was possible to examine with care the point raised above.

(II.) *Investigation of the Ultraviolet Region with a Fluorite Spectrograph.*

The general characteristics of the fluorite spectrograph will readily be seen from the sketch shown in Fig. 3, and the instrument as in actual use is shown in the photographic reproductions of Fig. 4 and Fig. 5. The prism was mounted in a central brass chamber from the two opposite sides of which projected a brass collimator tube and a brass tube terminated by a plate holder. This latter consisted of a shallow rectangular box carrying a frame which could be slightly rotated when adjustment was necessary. The box was provided with an opening at one end through which the photographic plate could be slipped into position. When the plate was in position and ready for an exposure the opening was closed with a small brass cap, and the joint made airtight by means of a rubber washer. The operation of inserting the plate and of closing the opening in the plate-holder was, of course, carried out in the dark. The photographic plates used were narrow strips cut from Schumann plates recently prepared and put on the market by the Adam Hilger Co.

In the course of the experiments it was found necessary to remove all water vapour from the spectrograph, in order to secure the best photographic results in the region of the shorter wave lengths. For that purpose a large cylindrical brass drying chamber, shown in Fig. 3, was attached to the collimator tube. Through an opening in one end of this chamber it was possible to insert or remove when desired a shallow tray filled with phosphorus pentoxide. The plate *P*, Fig. 3, provided with a rubber washer, enabled one to close the opening quite satisfactorily. The collimator tube was provided with two closely fitting tubes *A* and *B*, concentric with it. One of these, *A*, carried a disc, in which was inserted the condensing fluorite lens and the other, *B*, carried a plate to which the slit jaws were attached. The focussing lens was carried on a disc borne by a sliding tube, *E*, similar to *A* and *B*. The edges of the discs which carried the lenses were pierced

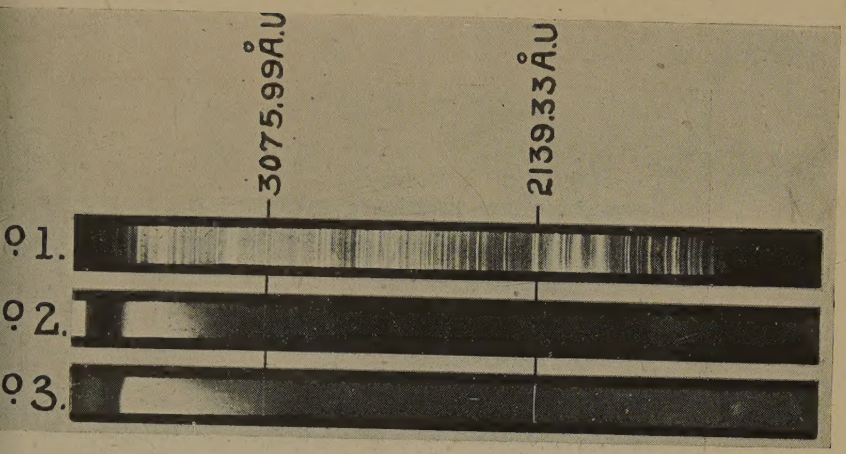

FIG. 1

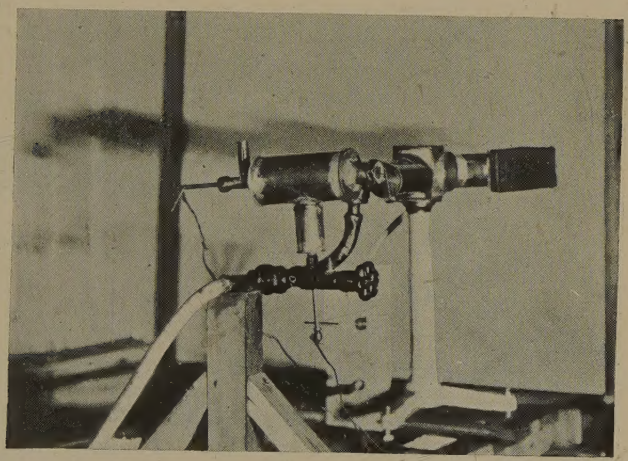

FIG. 4.

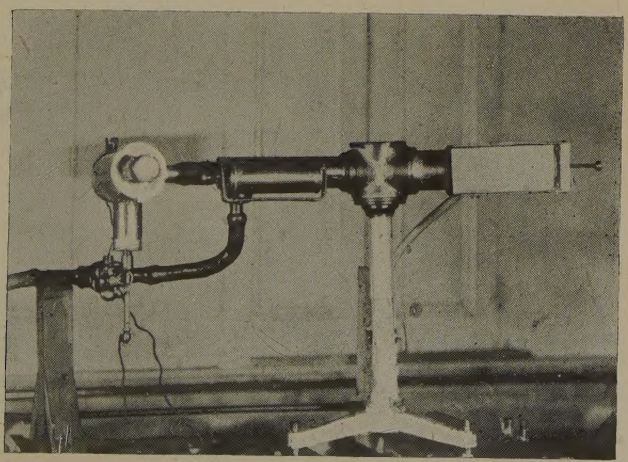

FIG 5.

[*To face* p. 6.

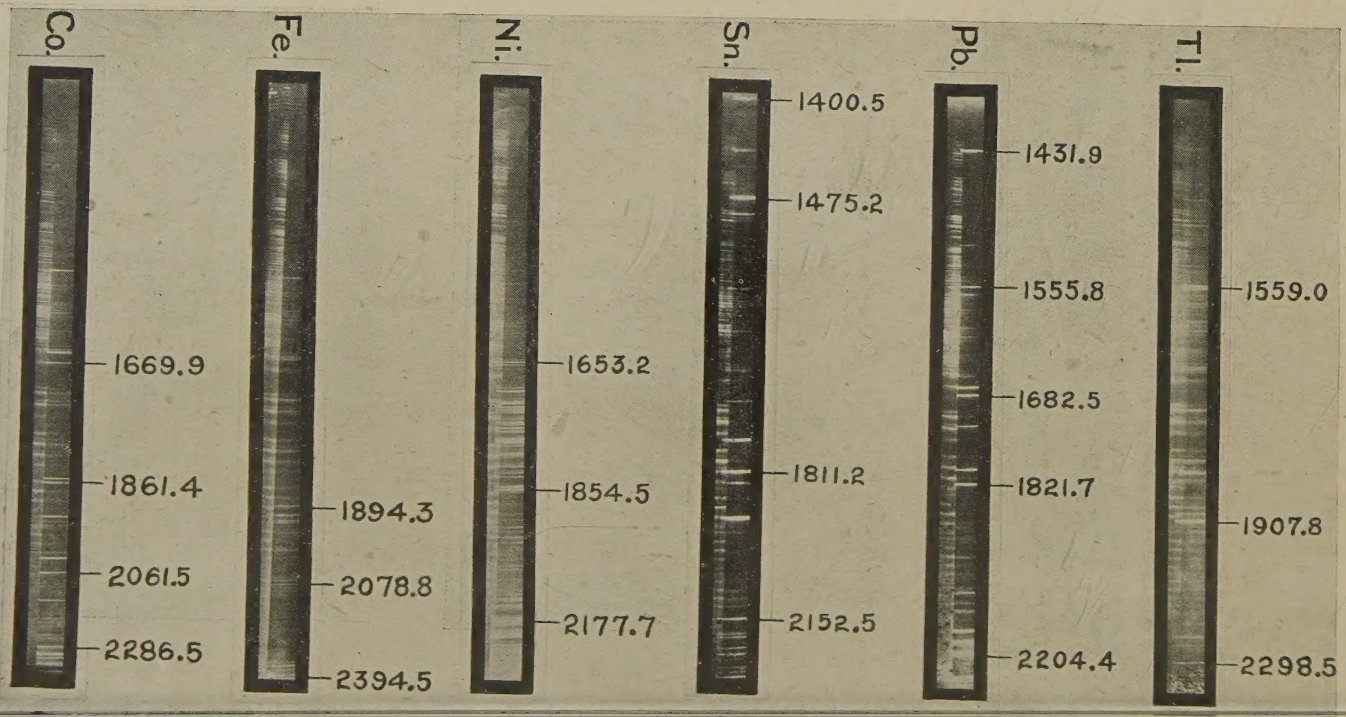
Co.
1669.9
1861.4
2061.5
2286.5
Fe.
1894.3
2078.8
2394.5
Ni.
1653.2
1854.5
2177.7
Sn.
1400.5
1475.2
1811.2
2152.5
Pb.
1431.9
1555.8
1682.5
1821.7
2204.4
Tl.
1559.0
1907.8
2298.5

FIG. 6.

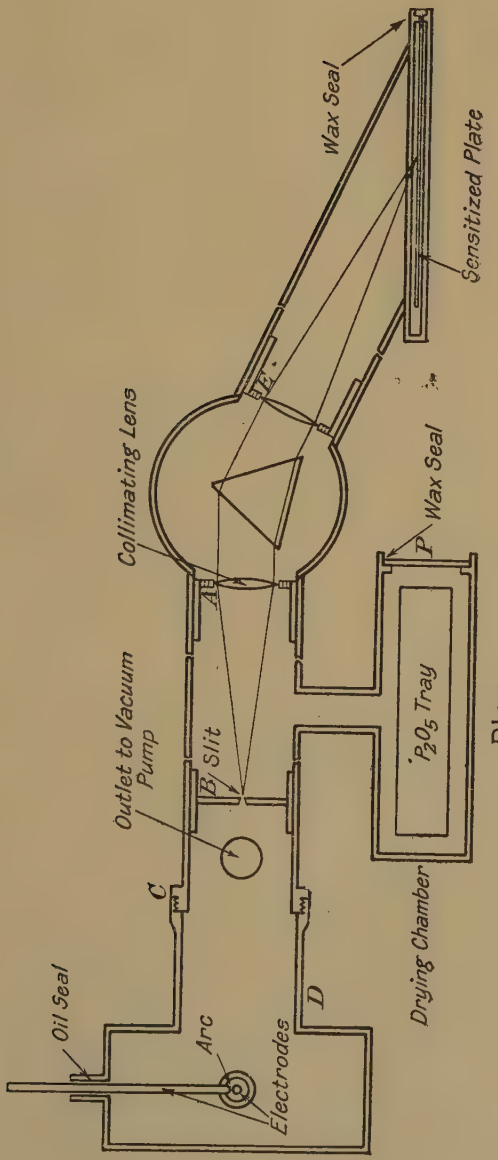
Wax Seal
Sensitized Plate
Collimating Lens
Wax Seal
Outlet to Vacuum Pump
Slit
P_2O_5 Tray
Oil Seal
Arc
Electrodes
Drying Chamber
Plan.

FIG. 3.

with a number of holes so that the air had free access through them to all parts of the instrument. The air was removed from the apparatus by means of a set of oil-sealed mechanical Trimount pumps, the connections being made with lead piping at the points shown in Fig. 3. The reproductions shown in Fig. 6 will serve to show the character of the results obtainable with arcs in vacuum between electrodes of thallium, lead, tin, nickel, iron and cobalt. The hydrogen spectrum is shown accompanying each reproduction. From the spectrograms it will be seen that wave lengths down to $\lambda=1400$ Å.U. were readily recorded.

(III.) *Investigation of the Extreme Ultraviolet Region with a Vacuum Grating Spectrograph.*

The vacuum grating spectrograph was designed by and obtained from the Adam Hilger Co. A sectional plan and sectional elevation of this instrument are shown in Fig. 7. Sketches of the grating mounting are shown in Fig. 8 and others of the slits, slit taps, auto-collimating eye-piece and film-carrying tap are given in Fig. 9.

The various parts with their designating letters are as follows :—

A. Tinned brass tube.
B. Ground end plate.
C, Grating carriage.
D. Rails for carriage.
E. Ruled diffraction grating : 20,000 lines per inch, 120 cm. radius.
F. Tube with ground fitting for exhaust.
G. Large ground tap containing film carrier.
H. Photographic film, Schumann sensitised.
I. Auto-collimating eye-piece.
J. Glass right-angled prism.
K. Slit.
L. Exhaust tube for film carrier.
M. Aperture for loading film carrier.
N Ground fitting for eye-piece, replaced by ground plug in working.
O. Ground taps for exposing through slit.
Q. Screw for adjusting vertical inclination of grating.
R. Micrometer screw for setting orientation of grating.
S Mount for diffraction grating.

The spectrograph was formed of a brass tube (*A*) 115 cm. long, 15 cm. in diameter and 3·5 mm. thick. At one end there was a cover (*B*) ground in and soldered and at the other a casting containing the slit and film holder. The slits (*K*), of which there were two 5·5 cm. apart, were mounted in a recess in the casting, and kept airtight when desired by a window. Each slit was provided with a tap (*O*) to enable

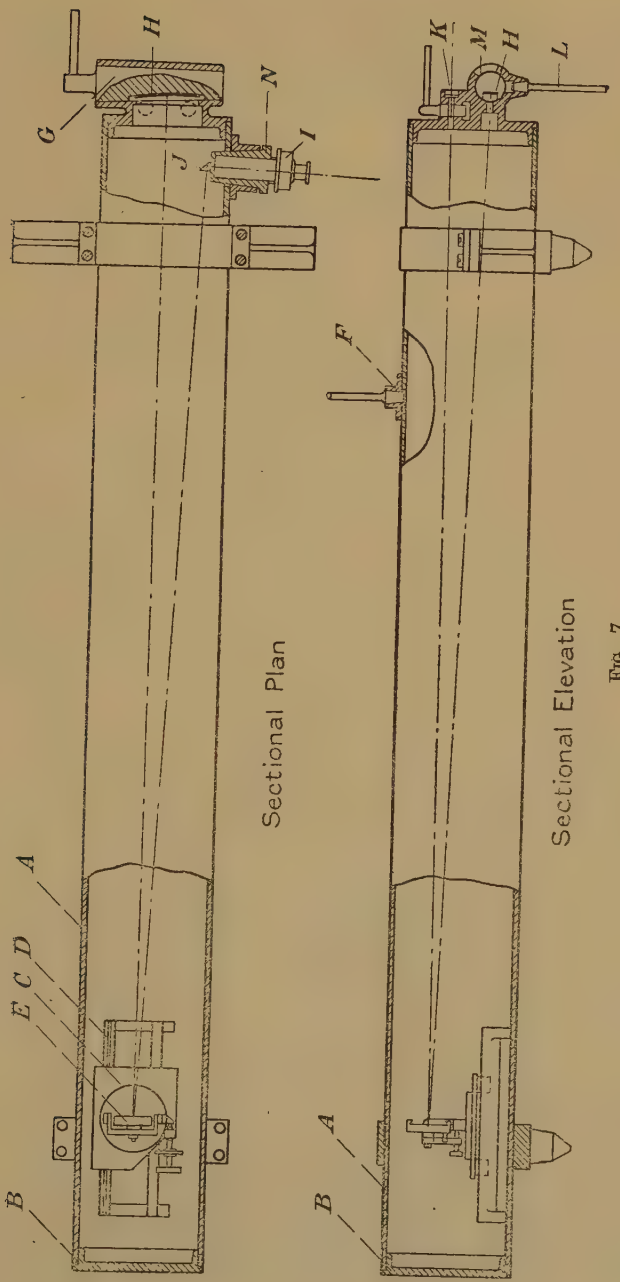

FIG. 7.

exposures to be made. The film (H) was carried in the main tap (G). The tap body had an aperture (M) to enable the film carried to be loaded, and an exhaust tube (L) to exhaust

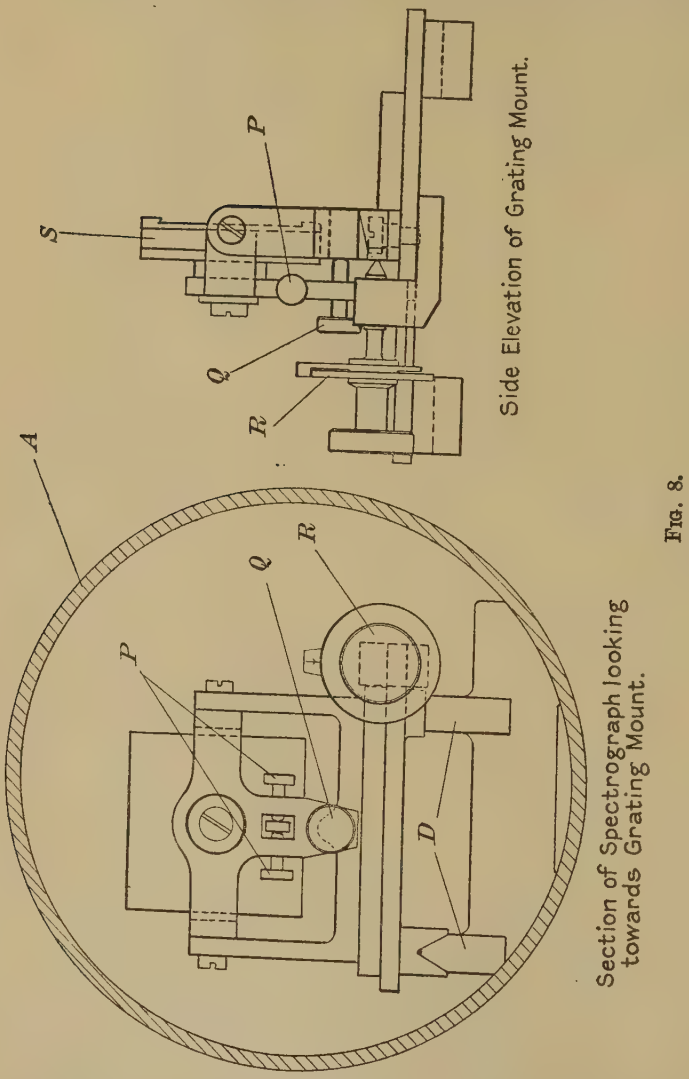

FIG. 8.

the film carrier before the exposure was made. This ingenious arrangement was intended to make it possible to introduce a plate without losing the vacuum in the main tube.

At the slit and film end of the tube on one side there was a mount for an auto-collimating eye-piece (*I*) and prism (*J*) mounted in a taper plug (*N*). When not in use the plug (*N*) with eye-piece and prism were withdrawn complete and replaced by a solid plug.

At the other end of the tube were rails (*D*) on which slid a carriage (*C*) carrying the grating mount (*S*). The length of

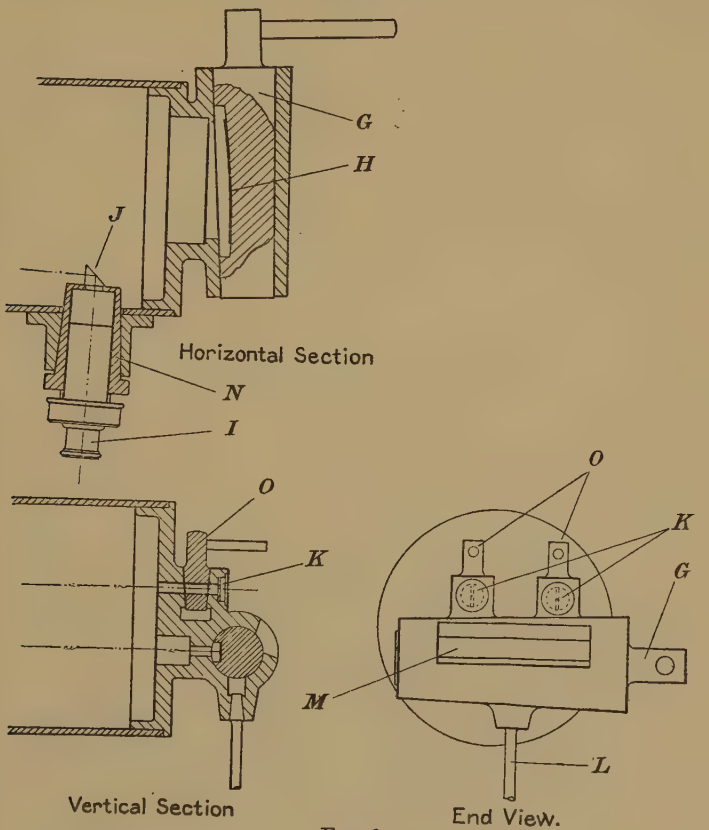

FIG. 9.

rails was sufficient to allow about 10 cm. travel for the carriage. The ruled grating No. 106 was 2·5 cm. wide and 1·9 cm. high. Its radius of curvature was 120 cm. and its ruling consisted of 20,000 lines to the inch. The mount was provided with adjusting screws (*P*) for setting the lines of the grating parallel to the slit, an adjusting screw (*Q*) for vertical

inclination of grating, and a micrometer screw for setting orientation of grating. The tilt of the grating and also of the film was 3° 13′.

The main exhaust pipe (*F*) was situated near the slit and film end of the tube and the volume to be exhausted was about 23·5 litres.

The inside of the main tube and all brass work in its interior were tinned; in the case of ground fittings, such as the taps (*G*) and (*O*), the grinding was done after tinning.

It was found exceedingly difficult to secure complete absence of porosity by tinning, and in the end this was accomplished by painting the whole of the exterior of the main tube with a thin layer of heated Chatterton's compound. In the course of the work it was found to be an advantage to paint the whole of the interior surface of the large tube a dull black to prevent reflections, and a number of diaphragms were placed at equal distances throughout its length for the same purpose.

A cylinder made of brass tubing 30 cm. long and 10 cm. in diameter, and not shown in the drawings, was connected to the main spectrograph tube by means of a short tube of large diameter. Through an opening in the end of this smaller cylinder a tray containing a thin layer of P_2O_5, and covered with glass wool could be inserted or withdrawn as desired. To secure the best results it was found necessary to remove all water vapour from the interior of the apparatus. Before making exposures with the arrangement described considerable quantities of phosphorus pentoxide were used, and this removed the vapour very rapidly when each exhaustion was made. The opening through which the tray was inserted was closed with a brass plate and made airtight with the Chatterton compound.

The photographic plates used were of the Schumann type, manufactured by the Adam Hilger Co. They were cut as desired from larger plates, and were about 5 mm. in width and 8 cm. in length. About 700 Å.U. was the range which it was possible to investigate with one slit without shifting the grating. The plate holder was of such a construction that the thin plates when inserted in the holder were bent to an arc of the circle, which included the ruling of the grating.

In making the exhaustions two Trimount oil pumps in series, run at 250 revs. per min. were used. To test the character of the vacuum obtained from time to time, a short

glass vacuum tube was sealed by a side tube into an opening made in the side of the spectrograph main tube. A discharge from a small induction coil was sent at intervals through the vacuum tube, and the appearance of the discharge gave an indication of the pressure within the apparatus.

Connection from the spectrograph to the pumps was made through a lead pipe of about 1 in. diameter provided with a $\frac{3}{4}$ in. Jenkins disc steam valve. This steam valve, which was provided with an oil seal as well as the usual stuffing box arrangement around the stem, worked very satisfactorily.

In practice it was found impossible to keep the ground joint made by the tap *G* with its matrix perfectly airtight at every point without coating all exposed parts of the joint with wax. In turning the tap to expose a plate this wax coating was always broken, with the result that leaks occurred. After spending considerable time trying to rectify this defect, the best results were finally obtained by abandoning the idea of

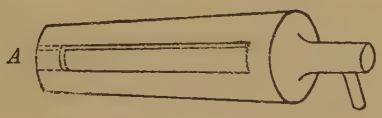

FIG. 10.

exhausting the plate-holder space in the tap *G* preliminary to turning the latter, so as to expose the plate.

The tap *G*, as originally provided with the apparatus, was replaced by a second one shown in Fig. 10. This large tap carried the plate holder as the original one did, and instead of the plate holder being inserted in a recess in the side of the tap as formerly the tap was slotted out to one end as shown at *A* in Fig. 10. This allowed the plate holder mounted on a thin brass strip to be inserted from the end *A*. When the plate was inserted the opening was covered with a small brass disc, which was sealed about its edge with wax. With this arrangement the tap always had its plate-holding recess facing the grating and ready for an exposure. The exposed parts of the tap joint were permanently covered with a wax coating to secure air-tightness.

The use of the special tap necessitated the re-exhausting of the whole apparatus, each time an exposure was made.

The Trimount pumps, however, were very rapid and efficient in action, and it was found comparatively easy to reach

with half an hour's continuous running, a pressure low enough for the induction coil discharge to give green fluorescence in the pressure testing vacuum tube. The reproductions shown in Fig. 11 serve to indicate the results obtainable with the instrument. The preliminary photographic work was chiefly done with arcs in vacuum between carbon terminals, and, as the reproductions show, the spectrum of this element was investigated as far down as 584 Å.U.

(IV.) *Ionisation Potentials.*

Referring again to Frank and Hertz's experiments, it will be recalled that they found that when mercury vapour was bombarded by electrons with a mean impact voltage of 4·9 volts, it became conducting, and they concluded from this that 4·9 volts was the ionisation potential for mercury atoms. They also found, as stated above, that the same impact voltage just sufficed to stimulate the vapour to the emission of monochromatic radiation of wave length $\lambda=2536{\cdot}72$ Å.U., which latter is in accordance with the requirements of quantum theory. If, however, the Bohr theory, that radiation of a definite frequency is emitted by an electron as it returns from an outer stationary orbit to an inner one, be accepted as the explanation of the origin of the emission of radiation giving a line spectrum by a nucleus atom of the Rutherford type, then Frank and Hertz's interpretation of their experiments leads us into difficulty, for it is impossible to hold Bohr's theory of the origin of radiation to be true, including acceptance of the quantum principle, and at the same time to hold the view that impact voltages which would just stimulate atoms to the emission of radiation consisting of one wave length will also suffice to ionise these atoms. An atom which is ionised is one which has had one or more of its electrons removed beyond its outermost stationary orbit. Consequently, if an atom be ionised it is in a condition to emit not a single line spectrum, but a spectrum consisting at least of one whole series of lines. In my early experiments I pointed out that my experiments led me to the view that if ionisation of mercury vapour was really brought about with an impact voltage of 4·9 volts, then an impact voltage of about 10·4 volts produced a *second* type of ionisation. I also pointed out that this type of ionisation was in accordance with the Bohr theory of the origin of radiation, because an impact voltage of 10·4 volts was just sufficient to establish an arc in the vapour, and so bring out the

many lined spectrum of the element. As already pointed out, the matter has been cleared up to a certain extent by the experiments of Bergen Davis and Goucher, for these experimenters have shown that the real ionisation potential of mercury vapour is about 10·4 volts, and that the conductivity which Frank and Hertz observed, with impact voltage of 4·9 volts, was not due directly to the bombarding electrons, but was due to the photo-electric reaction of the radiation of wave length λ=2536·72 Å.U. stimulated by the electric bombardment of the vapour. Bergen Davis and Goucher take the view that this photo-electric conductivity has its origin at the surface of the metallic electrodes upon which the radiation fell. It may conceivably, too, have had an origin, in part, at least, in condensed layers of mercury vapour in the neighbourhood of the cathode, for Derieux * has recently shown that the long wave length limit for the production of the photo-electric effect with mercury droplets is greater than λ=2536·72 Å.U. and less than λ=3126 Å.U., and is probably, therefore, about λ=2800 Å.U.

Tate † and Bishop ‡ have also recently confirmed experimentally the results of Bergen Davis and Goucher, and it now appears to be settled that 10·4 volts is the real ionisation potential of mercury atoms. It follows, therefore, that we have in this conclusion regarding the ionisation potential for mercury strong support for the view put forward by me that impact voltages which just suffice to establish arcs in metallic vapours when electronic streams of moderate density are used are exactly the same in magnitude as the ionisation potentials for the atoms of these vapours.

Going one step further, we see that since with mercury, zinc, cadmium and magnesium vapours the arcing potentials with streams of electrons of moderate density have been shown to be practically identical with the P.D.s given by the quantum equation for the frequencies $\nu=(1\cdot5, S)$ of the spectra of these vapours, it follows that of all the wave lengths in the spectra of at least a number of the elements those whose frequencies are given by $\nu=(1\cdot5, S)-(m, P)$, and possibly, too, by $\nu=(1\cdot5, S)-(m, p_2)$, are of fundamental importance. A knowledge of the wave lengths of these in the spectrum of an element, enables us to calculate the frequency $\nu=(1\cdot5, S)$ for

* Derieux, " Phys. Rev.," Vol. XI., No. 4, p. 276, April, 1918.
† Tate, " Phys. Rev.," Vol. X., No. 1, p. 81, July, 1917.
‡ Bishop, " Phys. Rev.," Vol. X., No. 3, p. 244, Sept., 1917

that element, and consequently enables us to calculate the ionisation potential for it. We can, therefore, follow any one of three paths in determining the ionisation potential of an element, namely, (1) by determining the minimum arcing potential for its vapour, (2) by using a special electrical method, such as that designed by Bergen Davis and Goucher, or (3) by determining for the element the wave lengths in its spectrum, which constitute the series $\nu=(1{\cdot}5,\ S)-(m,\ P)$.

The first method, as will be seen later, is apt to lead us into error, for the conditions which should be fulfilled in experimentally determining minimum arcing potentials are not so well defined as was at first supposed. The second method can only be used with gases or with metals which can be vaporised at comparatively low temperatures. The third method is probably the one which admits of widest application. An attempt should therefore be made to identify the wave lengths of the series $\nu=(1{\cdot}5,\ S)-(m,\ P)$ in the spectra of as many of the elements as possible. Up till recently the series was known only for mercury, zinc, cadmium, magnesium, calcium and strontium. For many of the elements the series, or a majority of the members of it, lies in the ultra violet or in the extreme ultra violet region of the spectrum, and consequently the investigation is fraught with some difficulty. If the requisite optical apparatus be available one method to follow is to use the Zeeman effect to identify the series. Another method which may be used is to take advantage of the phenomenon of absorption. For the elements for which the series is known the wave lengths constituting the series $\nu=(1{\cdot}5,\ S)-(m,\ P)$ are strongly absorbed by the non-luminous vapour of these elements. It may be that this characteristic is fundamental and a property of the elements generally. If it should turn out to be so the utilisation of absorption would appear to be the easiest method of spotting the series. Quite recently, in collaboration with Mr. J. F. T. Young,* I found the method applicable not only for calcium and strontium, but for barium as well. In the application of the method it was found that if a small quantity of the metal or of one of its salts were vaporised in a carbon arc, it was possible to obtain reversals with certain densities of vapour at only those wave lengths which constituted the $\nu=(1{\cdot}5,\ S)-(m,\ P)$ series. Reproductions showing the results obtained are given in Figs. 12, 13

* McLennan and Young. Communicated to the Royal Society, Oct., 1918.

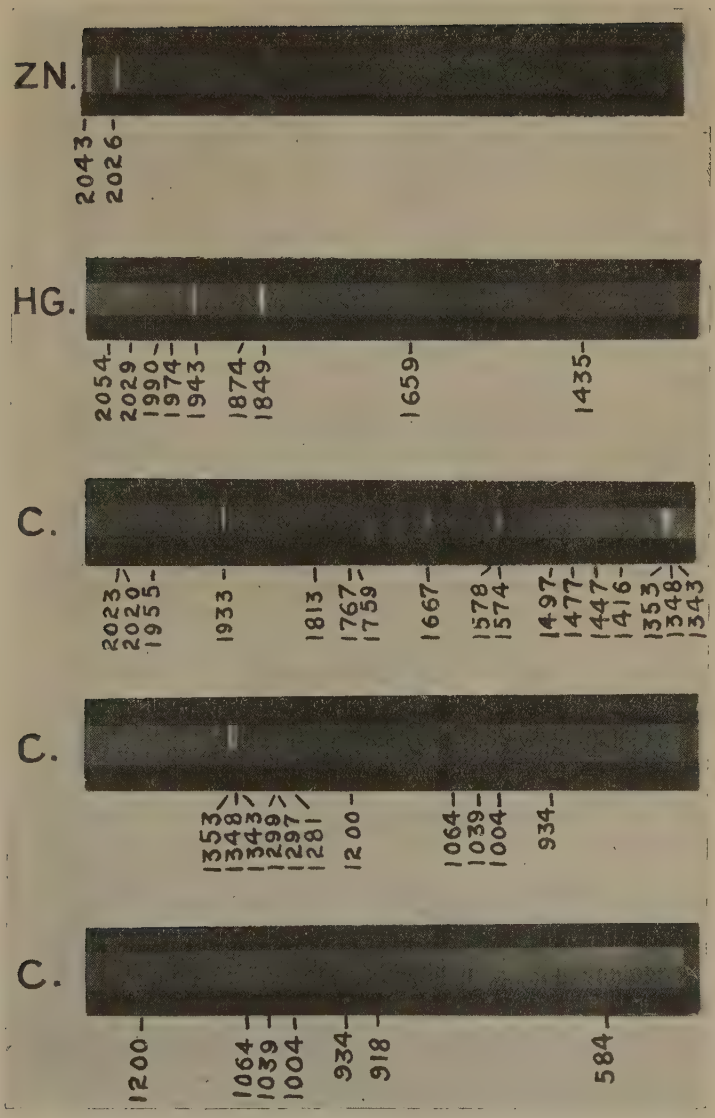

FIG. 11.

[*To face p. 16.*

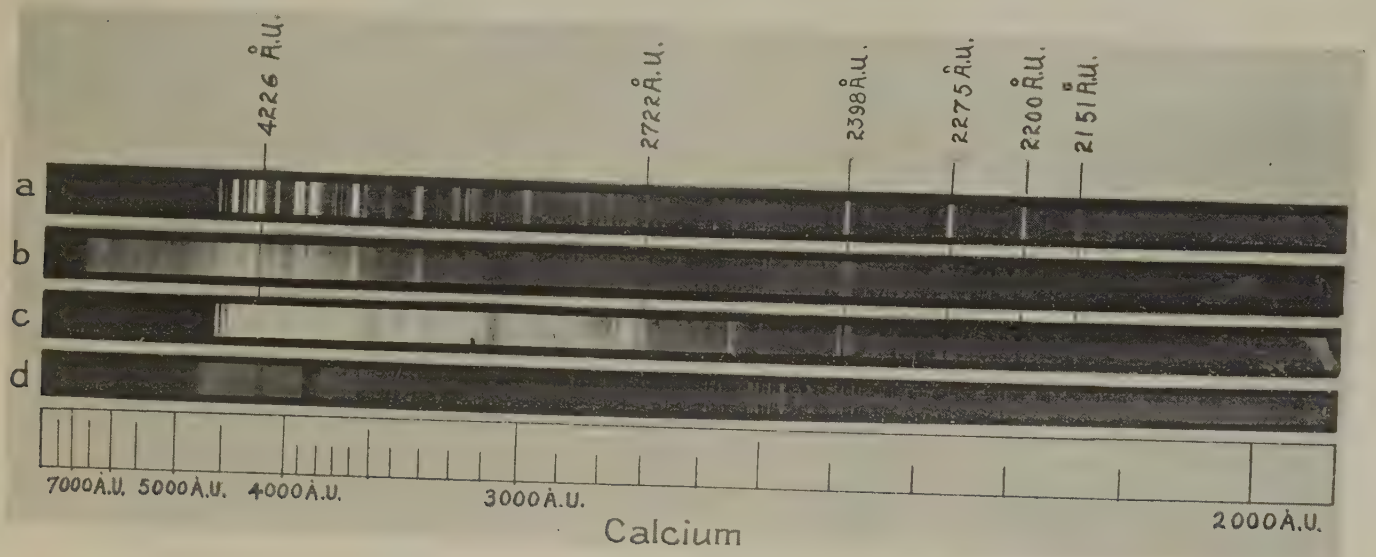
4226 Å.U.
2722 Å.U.
2398 Å.U.
2275 Å.U.
2200 Å.U.
2151 Å.U.
a
b
c
d
7000 Å.U.
5000 Å.U.
4000 Å.U.
3000 Å.U.
2000 Å.U.
Calcium

Fig. 12.

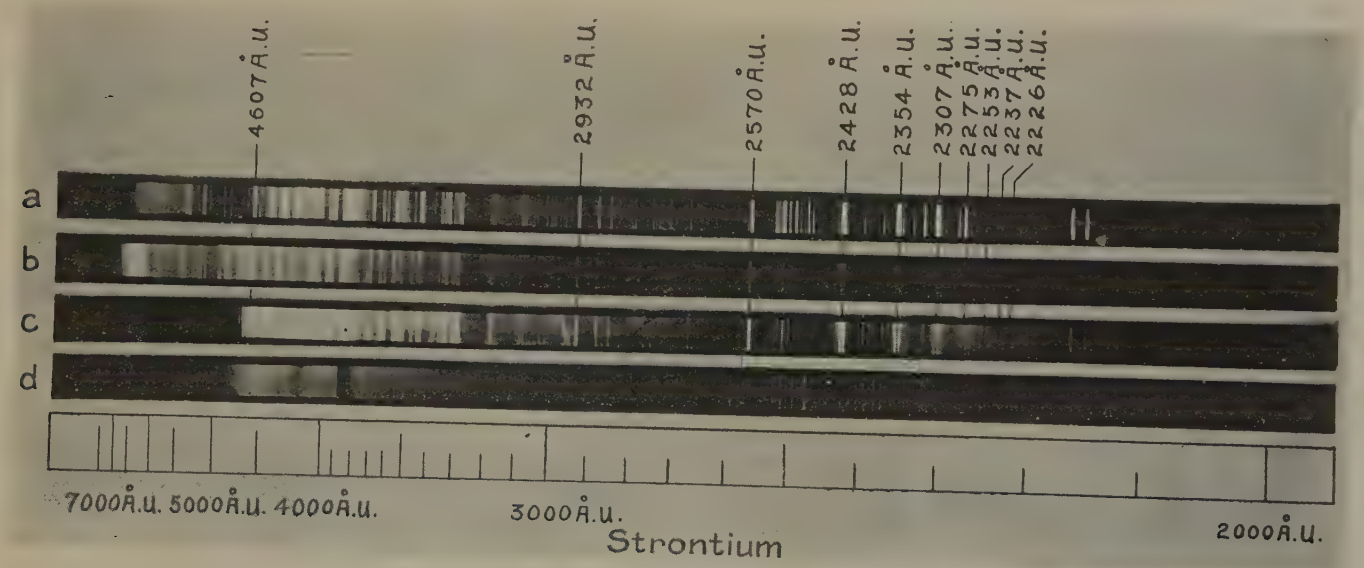
4607Å.U.
2932Å.U.
2570Å.U.
2428Å.U.
2354Å.U.
2307Å.U.
2275Å.U.
2253Å.U.
2237Å.U.
2226Å.U.
a
b
c
d
7000Å.U. 5000Å.U. 4000Å.U.
3000Å.U.
2000Å.U.
Strontium

Fig. 13.

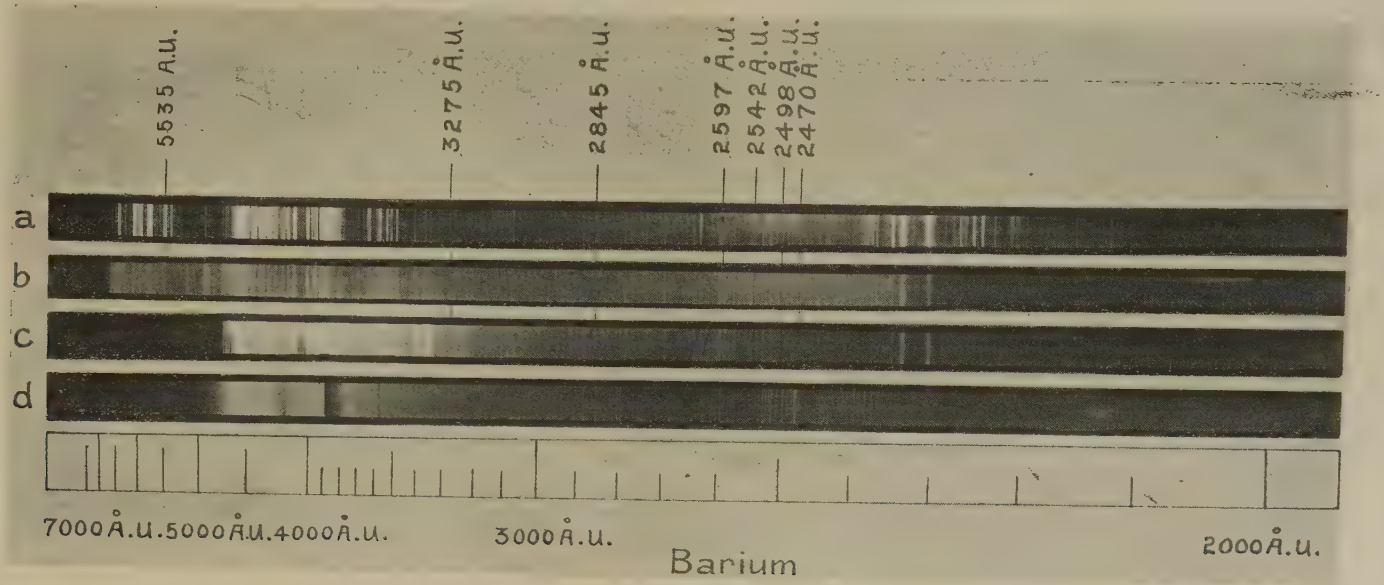
5535 A.U.
3275 Å.U.
2845 Å.U.
2597 Å.U.
2542 Å.U.
2498 Å.U.
2470 Å.U.
a
b
c
d
7000 Å.U. 5000 Å.U. 4000 Å.U.
3000 Å.U.
2000 Å.U.
Barium

FIG. 14.

and 14. In each set of reproductions (*a*) is the emission spectrum of the metal taken with a Schumann plate, (*b*) is the absorption spectrum of the metal taken on a panchromatic plate, (*c*) is its absorption spectrum taken with a Schumann plate, and (*d*) is the emission spectrum of the carbon arc alone.

From these experiments the wave lengths of the series $\nu=(1{\cdot}5, S)-(m, P)$ for barium are now known to be as follows :

Barium.

Series $\nu=(1{\cdot}5, S)-(m, P)$.

$m=$	2	3	4	5	6	7	8	9	10
λ(Å.U.)=	5535	3275	2845	2597	2542	2498	2470	2455	2441
$\nu=$	10864·6	30534·4	35149·4	38502·1	39339·1	40032	40486	40733·2	40966·8

The limiting frequency $\nu=(1{\cdot}5, S)$ for the series comes out by calculation to be 42006·85, and the corresponding shortest wave length of the series is given by $\lambda=2380{\cdot}56$ Å.U. This leads to an evaluation of the ionisation potential for barium, which has been deduced to be 5·21 volts. In passing, it may be noted that the discovery of the series $\nu=(1{\cdot}5, S)-(m, P)$ for barium has enabled us to calculate the wave lengths of the two series $\nu=(2{\cdot}5, S)-(m, P)$ and $\nu=(3{\cdot}5, S)-(m, P)$ as well for the same element. It has also led us to predict that the wave length corresponding to the frequency $\nu=(1{\cdot}5, S)-(2, p_2)$ is approximately $\lambda=7901{\cdot}11$ Å.U.

The recent experiments of Tate and Foote * point the way for a direct determination of the ionisation potentials of the vapours of magnesium, calcium, strontium and barium, and it will be interesting to see whether the experimental values so obtained for these vapours agree with the values calculable for them from the limiting frequencies of the singlet series $\nu=(1{\cdot}5, S)-(m, P)$ of their spectra. The ionisation potentials for the different elements, in so far as they appear to be known have been collated and are given in Table II. Table III. also contains the ionisation potentials for a number of simple and compound gases and vapours which have been determined experimentally by Hughes and Dixon.

(V.) *Low-voltage Arcs in Metallic Vapours.*

In a Paper by Millikan† and in one by Hebb‡ experiments are described in which arcs were established in mercury vapour bombarded by electrons when the P.D.s applied were

* Tate and Foote, "Phil. Mag.," July, 1918, p. 64.
† Millikan, "Phys. Rev.," Vol. IX., No. 5, p. 378, 1917.
‡ Hebb, "Phys. Rev.," Vol. IX., No. 5, p. 371, 1917.

TABLE II.—*Ionisation Potentials.*

Element.	Values determined by direct experiment.*	Calculated values.†
Helium	20·5 volts.	29·3 volts.
Neon	16·0 ,,	—
Argon	12·0 ,,	—
Hydrogen	11·0 ,,	—
Oxygen	9·0 ,,	—
Nitrogen	7·9 ,,	—
Mercury	10·4 ,,	10·45 volts.
Zinc	9·5 ,,	9·4 ,,
Cadmium	8·92 ,,	9·0 ,,
Magnesium	—	7·65 ,,
Calcium	—	6·12 ,,
Strontium	—	5·70 ,,
Barium	—	5·21 ,,
Sodium	5·13 volts	5·13 ,,
Potassium	4·1 ,,	4·32 ,,

* Aston, "Proc." Roy. Soc., June 14, 1907; Frank and Hertz, "Ber." d Deut. Phys. Ges., Heft 2, p. 44, 1913; Bazzoni, "Phil. Mag.," Nov., 1916; Tate, "Phys. Rev.," Vol. X., No. 1, p. 81, 1917; Bergen Davis and Goucher, "Phys. Rev.," Vol. X., No. 2, p. 101, 1917 Bishop, "Phys. Rev.," Vol. X., No. 3, p. 244, 1917; Wood and Okano, "Phil. Mag.," Sept., 1917, p. 177; Tate and Foote, "Phil. Mag.," p. 64, July, 1918.

† Bohr, "Phil. Mag.," Vol. XXVIII., Feb., 1915; McLennan and Henderson, "Proc." Roy. Soc A, Vol. XCI., p. 485, 1915; McLennan, "Proc." Roy. Soc. A, Vol. XCII., p. 305, 1916; McLennan, "Phys. Rev.," Vol. X., No. 1, p. 84, 1917; Richardson and Bazzoni, "Phil. Mag.," Oct., 1917, p. 285; Tate and Foote, "Phil. Mag.," p. 64, July, 1918.

TABLE III.—*Ionisation Potentials by Hughes and Dixon.**

Vapour or gas.	Ionisation potential.
H_2	10·2 volts.
O_2	9·2 ,,
N_2	7·7 ,,
S	8·3 ,,
Cl_2	8·2 ,,
Br_2	10·0 ,,
Hg	10·2 ,,
HCl_1	9·5 ,,
CO	7·2 ,,
CO_2	10·0 ,,
NO	9·3 ,,
CH_4	9·5 ,,
C_2H_6	10·0 ,,
C_2H_4	9·9 ,,
C_2H_2	9·9 ,,

* Hughes and Dixon, "Phys. Rev.," Vol. X., No. 5, p. 495, 1917.

considerably less than those which the experiments of Bergen Davis and Goucher have indicated are requisite to accomplish the ionisation of mercury atoms.

In particular, Millikan and Hebb found that under certain specified experimental conditions it was possible to cause arcs to strike in mercury vapour with applied P.D.s as low as 4·7 volts. Moreover, they also found that arcs so struck could be maintained in the vapour when the applied field was reduced to as low as 3·2 volts. Hebb also found that it was possible under certain circumstances to cause the vapour to radiate monochromatic light of wave length $\lambda=2536{\cdot}72$ Å.U. when the applied field in which the electrons were projected was as low as 2·5 volts. As these results would appear to be in conflict with what should be expected on the quantum theory, namely, that the ionisation potential is given by $V=\frac{(1{\cdot}5, S).h}{e}$, where $(1{\cdot}5, S)$ is the frequency of the shortest wave length of the principal singlet series $\nu=(1{\cdot}5, S)-(m, P)$, it was considered necessary that the experiments should be repeated and the results either confirmed or disproved. With a view to doing this some experiments were recently made for me by Mr. R. Hamer and Mr. F. W. Kemp * in the Physical Laboratory at Toronto. In these the vapours of cadmium and zinc, as well as that of mercury, were used, and the results obtained go to confirm the findings of Millikan and Hebb. The main results of the investigation are as follows :—

1. It has been shown that increasing the temperature of the incandescent cathode lowers the voltage necessary to produce arcs in the vapours of mercury, zinc and cadmium.

2. With limed platinum cathodes arcing voltages were not obtained as low as with incandescent tungsten filaments.

3. With highly heated incandescent cathodes it was found that with vapour of low density the arcing potentials were high. When the density of the vapour was increased the arcing potentials fell, and reached a minimum value at a certain density of the vapour. When the density of the vapour was still further increased the values of the arcing potentials rose again.

4. The voltages necessary to maintain arcs in the vapours were found to be less than those which had to be applied in order to strike the arcs.

* McLennan. Communicated to The Physical Society of London, Oct., 1918.

5. With mercury it was found possible to strike arcs with arcing potentials as low as 4·75 volts, and to maintain them with an applied P.D. of 2·84 volts. With cadmium vapour arcs were struck with impact voltages of 5 volts, and maintained with P.D.s of 2 volts. To obtain these low-voltage arcs it was necessary to use intensely hot cathodes and a copious supply of highly heated metallic vapour.

6. In many of the experiments it was noticed that when certain voltages near the minimum ones were applied, no arc appeared in the vapours forthwith, but arcs did finally strike when an interval of time of greater or shorter length was allowed to elapse.

7. With moderately heated incandescent cathodes and a moderate supply of metallic vapour the arcing voltages with mercury, zinc, and cadmium vapours under electronic bombardment were given by the quantum relation. $V=\frac{(1\cdot5, S)\times h}{e}$, where $(1\cdot5, S)$ is the frequency of the shortest wave length in the $\nu=(1\cdot5, S)-(m, P)$ series.

8. In the experiments with cadmium vapour it was found to be possible to set up two types of arc in the vapour, the one being faint and the other brilliant. The line spectrum of the two types appeared to be the same in character, but different in intensity. Additions of P.D. in the applied field of not more than a volt generally sufficed to enable one to pass from the faint to the brilliant type. With the brilliant arcs a continuous white light spectrum was superimposed upon the line spectrum.

9. Irregularities in the experimental results were in a measure removed when the metal being vaporised, was kept electrically connected to the positive terminal of the discharge tube.

(VI.) *Discussion of Results.*

From the results of Bergen Davis and Goucher, combined with those of other investigators, it would appear to be generally agreed that with the vapours of such elements as mercury, zinc, cadmium and magnesium, for example, the actual ionisation potentials are given by $V=\frac{(1\cdot5,\ S)\times h}{e}$, where $(1\cdot5, S)$ is the frequency of the shortest wave length of the principal singlet series $V=(1\cdot5,\ S)-(m,\ P)$. The

ionisation potentials for the metals indicated are respectively 10·45 volts, 9·4 volts, 9 volts and 7·65 volts. It is also certain that when arcs are established in these vapours the atoms of the vapour of these elements are ionised. The experiments of Millikan, Hebb, Hamer and Kemp also clearly show that with the vapours of mercury and cadmium it is possible to strike arcs by electronic bombardment with incandescent cathodes when the applied impact voltages are as low as 4·75 volts with mercury and 5 volts with cadmium.

It is also evident that with mercury vapour arcs can be maintained with impact voltages as low as 2·84 volts, and with cadmium vapour with impact voltages as low as 2 volts. In the case of argon, Mackay and Fergusson * have also shown that with an incandescent tungsten cathode it is possible when the gas is carefully purified to maintain an arc with potential drops a little less than 4 volts, and that with the gas at a pressure of 5 cm. of mercury. This potential drop in the gas, it will be noted, is considerably less than the ionisation potential for argon, which is given by Frank and Hertz † as 12 volts.

The question then to be settled is, whence comes the energy requisite to produce ionisation in the case of these low-impact voltage stimulated arcs ?

Among others, two explanations have been put forward the one by Millikan and Hebb, ‡ involving the principle of "photo-electric radiation reaction," and the other by Van der Bijl, § involving the principle of "successive impacts."

According to the first mentioned explanation, we are to assume that with impact voltages of about 5 volts the kinetic energy of the bombarding electrons is sufficient to stimulate the vapour to the emission of the monochromatic radiation of frequency $\nu=(1\cdot5, S)-(2, p_2)$, which for mercury is $\lambda=2536\cdot72$ Å.U. and for cadmium is $\lambda=3260\cdot17$ Å.U. This monochromatic radiation is then supposed to react upon the incandescent cathode, and possibly, too, upon condensed layers of the vapour which may be present on the walls of the tube in the neighbourhood of the cathode, and so bring about the emission of electrons with initial speeds greater than those which the electrons would have from thermionic considerations alone. These highly speeded electrons would then,

* Mackay and Ferguson, "Journ." of the Franklin Institute, p. 209, Feb., 1916.

† Frank and Hertz, "Ber." d. Deutsch. Phys. Ges., XV., p. 34, 1914.

‡ Millikan and Hebb, loc. cit.

§ Van der Bijl, "Phys. Rev.," Vol. XI., No. 3, p. 170, March, 1918.

after passing through the applied electric field, be able to stimulate radiation of still shorter wave lengths than that of frequency $\nu=(1{\cdot}5,\ S)-(2,\ p_2)$, and this would in turn react upon the incandescent cathode and again cause the emission of electrons with still higher initial speeds. The result of the application of this principle, if it is a valid one, would be that in any case of radiation stimulated by electronic bombardment whenever impact voltages were applied, which would suffice to stimulate the radiation of frequency $\nu=(1{\cdot}5,\ S)-(2,\ p_2)$ all the conditions would be existent for the production of the many lined spectrum. There could be on this theory no such thing as a vapour under any conditions of density and temperature emitting a radiation consisting of one wave length and one wave length only. Again, according to the principle of " successive impacts " invoked by Van der Bijl, we are to suppose that the same atom can be successively bombarded by different electrons, and that as a result of these successive bombardments the atom ultimately becomes ionised. Van der Bijl adheres to the Bohr theory of the origin of radiation and supposes that although each bombarding electron may not possess sufficient kinetic energy to ionise an atom by itself, still, at each impact, the bombarding electron may be able to impart sufficient energy to the atom struck to cause one or more electrons of its system to be projected into a stationary atomic orbit with a larger radius than the one it was in before the atom struck. The potential energy of a bombarded atom would thus increase by stages under multiple impacts, and this would go on until ionisation occurred.

With the atoms ionised it would follow that the vapour was in the condition to emit radiation corresponding to the many lined spectrum. It will be seen, therefore, that the hypothesis of the principle of " successive impacts " also leads to the view that the radiation from a vapour when bombarded by electrons, be the density of the vapour high or low, cannot be monochromatic, but must be such as to give the many lined spectrum.

Another view to take of the matter is to suppose that the distribution of velocities among the electrons emitted by an intensely hot tungsten filament is such that a considerable number of these have initial velocities corresponding to potential falls of from 5 to 6 volts. If this be so it is not necessary to assume either the hypothesis of " radiation

reaction" or that of "successive impacts," for with applied fields of about 5 volts, the high-speed electrons mentioned above will, in the applied field, acquire sufficient kinetic energy to ionise the vapour. This view also leads, it will be seen, to the result that a vapour bombarded by such streams of electrons must emit a radiation which can not be monochromatic, but must be one which will produce the many lined spectrum.

As the distribution of velocities indicated above will depend only upon the temperature of the tungsten filamental cathode, it follows that even with very low densities the vapour bombarded must emit a panchromatic radiation.

All three hypotheses, therefore, lead to the same result, namely, that it is impossible to stimulate a vapour by electronic bombardment to the emission of a radiation of one particular wave length. This result would appear then to be in direct contradiction to the experimental results of McLennan and Henderson, McLennan and Ireton, Bergen Davis and Goucher, Tate and others who found that with vapour bombarded by streams of electrons of moderate density it was possible by using suitable impact voltages to obtain radiation from the vapour which registered on the photographic plates, even with hours of exposure, only a single wave length. The contradiction may turn out, however, to be only apparent, for it may well be that while the average or mean speed of the electrons bombarding the vapour may suffice to bring out a radiation of one wave length with comparatively strong intensity the number of electrons possessing velocities higher than the mean falls off so rapidly with the higher speeds that, under the ordinary conditions which obtain, the amount of energy associated with the radiations of wave length shorter than the first one is too excessively small to be detected photo-electrically or photographically. The effects of absorption also come in, and add to the difficulty of obtaining indications of the presence of the shorter wave lengths. This view would fit in both with the results of Bergen Davis and Goucher with mercury vapour, as well as with those of McLennan and Ireton with zinc and cadmium vapours, in which it was found that with certain applied voltages given by the quantum relation it was possible to register an emission of radiation of one wave length only from the vapour bombarded and by gradually increasing the impact voltages to bring out a second radiation of a shorter

wave length which again corresponded to the quantum relation. To account for this result it is only necessary to suppose that by far the greater number of electrons leave the incandescent cathode with zero initial velocities. All the recent experimental work on the production of characteristic radiations from metals bombarded in a vacuum by electrons points to the accuracy of this view, for it has been definitely shown that a given characteristic radiation is given out only when the impact voltages of the electrons reach the value given by the quantum relation for this particular radiation. Richardson's theory of the thermionic emission of electrons makes it abundantly clear that while the great majority of the electrons may leave an incandescent filament with very small velocities still certain percentages will be emitted with velocities ranging practically to infinity. The fractions possessing the higher velocities are, however, necessarily small. Various estimates have been formed of the average speed of emission of the electrons from an incandescent filament. Among others, Richardson and Brown * place the average velocity of emission of electrons from an incandescent platinum filament at 0·6 volt, and from a limed platinum filament at 1·2 volts. Wood and Okano † give 0·4 volt as the average velocity with which electrons leave an incandescent tungsten wire, but Tate and Foote ‡ point out that one explanation of their results requires the average velocity of emission to be 1·6 volts. Both Wood and Okano and Tate and Foote have expressed the view that an appreciable fraction of the electrons are emitted with velocities still higher than the equivalent of 1·6 volts potential drop. Hebb § suggests 2 to 3 volts as possibly representing under certain circumstances the velocity of electronic emission. It seems legitimate then to assume that while the most important of the effects produced by the electronic bombardment of a vapour may demand a zero initial velocity for the electronic emission from an incandescent cathode still it is conceivable that other effects of a less pronounced character may be brought into evidence under special conditions which indicate that an appreciable fraction of the electrons emitted from a highly heated incandescent tungsten filament may leave it with very considerable initial

* Richardson and Brown, "Phil. Mag.," Vol. XVI., 1908.
† Wood and Okano, "Phil. Mag.," Sept., 1917.
‡ Tate and Foote, "Phil. Mag.," July, 1918.
§ Hebb, "Phys. Rev.," May, 1917.

velocities. Take, for example, the case of mercury and cadmium vapours stimulated under electronic bombardment to the emission of a radiation giving their many lined spectra when impact fields as low as 5 volts were used. Here it is only necessary to assume that small but appreciable fractions of the bombarding electrons possess initial thermionic velocities as high as the equivalent of about 5 volts. That this is conceivable would seem to be warranted by the evidence adduced above.

For the stimulation of a vapour to the emission of panchromatic radiation by electronic bombardment with low impact voltages without the production of so-called arcs in the vapour, the requisite conditions would appear to embrace the use of vapours of comparatively high density and the use of intensely dense streams of electrons from an extremely hot incandescent cathode. These, it will be recalled, are exactly the conditions which applied in the experiments of Kemp, in which he obtained with low fields the many lined spectrum from cadmium vapour without any trace of the presence in the background of a white light spectrum, and with a marked absence of the great brilliancy which usually characterises the line spectrum of an arc.

The argument which has been developed above leads, it will be seen, to the view that the emission from a vapour bombarded by electrons of a radiation consisting of the wave lengths which make up its line spectrum does not necessarily connote the simultaneous existence of a so-called arc in the vapour. As actual arcs can be struck in metallic vapours bombarded by electrons with low-impact voltage fields it is necessary, however, in order to explain their production, to invoke the agency of factors other than the streams of electrons which owe their existence to thermionic emission from the incandescent cathode. These latter, it will be seen, suffice on the view presented to produce, in conjunction with low fields, ionisation in the vapour and the consequent emission of a radiation giving the many lined spectrum, but for the production of arcs as they are ordinarily observed, we must look in another direction for an additional supply of electrons. A possible source of such a supply is afforded by the presence in the vapour of positive ions formed by the primary thermionically emitted electrons when these are accelerated in the applied field.

With an applied field of about 5 volts it would be impossible to give these positive ions sufficient kinetic energy to ionise the atoms of mercury vapour, for example, assuming the ionisation potential of the latter to be 10·4 volts. It is conceivable, however, that they could acquire sufficient kinetic energy in the electric field to produce when impinging upon the incandescent cathode an emission of electrons from the latter with initial velocities so high that on passing through the electric field they acquired additional kinetic energy sufficient to bring about ionisation of the vapour. If the quantum relation applied to this hypothetical emission of electrons from the cathode under bombardment by the positive ions the highest mean initial kinetic energy that the emitted electrons could have would be that represented by a potential fall of about 5 volts. Consequently, the highest kinetic energy that these electrons could acquire in passing through the electric field would be that corresponding to about 10 volts, which is practically the ionisation potential of mercury atoms. If, then, the positive ions are to be considered as playing a main rôle in the production of arcs in vapours bombarded by thermionically emitted electrons it is evident that one could not hope to strike arcs in these vapours with applied impact voltages smaller in magnitude than one-half the value of the ionisation potentials of these vapours. As the ionisation potentials for mercury vapour and for cadmium vapour are probably 10·4 volts and 9·4 volts respectively, and as it was found that the lowest impact voltages with which arcs could be struck in these vapours were respectively 4·75 and 5 volts, this result would seem to indicate that the positive ions do play an important part, in the manner indicated, in bringing about the establishment of the arcs. The explanation of the fact that arcs when once struck in a vapour can be maintained with lower applied fields than the minimum ones which are requisite to cause the arcs to strike, is not altogether clear. This phenomenon, however, is not confined to vapours alone, since it is known to characterise arc discharges in gases generally. Factors such as thermionic emission from the hot gases or vapours, thermal molecular agitation, and possibly chemical action as well, may have a bearing on the matter. It is to be remembered, too, that when once an arc has been established in a vapour or in a gas, the molecules are no longer in their normal state. Consequently, the considerations which apply in dealing with

the question of the maintenance of arcs may be quite different from those which apply in an explanation of their initial production.

(VII.) *General Results.*

Among the general results which appear to emerge as unassailable from the investigations dealt with in the present communication is the view that the ionisation potential is a definite and determinate magnitude, varying with and characterising each particular type of atom. It would also appear that, while this magnitude may be determined experimentally for each element, provided the requisite physical conditions can be realised, it can also probably be deduced by the quantum theory from a knowledge of the value of the frequency $\nu=(1\cdot5, S)$ of the shortest wave length in the principal singlet series $\nu=(1\cdot5, S)-(m, P)$ of the spectrum of the element. It would also appear to be established that it is possible to cause a vapour bombarded in a vacuum by electrons to emit a radiation consisting of one wave length and one wave length only, provided *all* the bombarding electrons possess kinetic energy given by the quantum relation $Ve=h\nu$, ν being the frequency of the monochromatic radiation stimulated ; moreover, it would appear that by gradually increasing the speed of the bombarding electrons the vapour may be caused to emit at successive stages radiation of shorter and shorter wave lengths, each particular wave length being stimulated only when the bombarding electrons have attained velocities corresponding to its frequency as indicated by the quantum relation. All apparent departures from this view obtained in any experiments would appear to be explainable when account is taken of the fact that a Maxwellian distribution of velocities holds for streams of electrons thermionically emitted by incandescent metallic filaments.

(VIII.) *Infra red Stimulation and Two Type Ionisation Potentials.*

The inquiry into the origin of radiation described above has recently been given as impetus in another direction by some results obtained in the infra red region of the spectrum by one of my students, Mr. R. C. Dearle,* at Toronto. In 1913 attention was specially drawn in a Paper by McLennan and

* Dearle ," Roy. Soc.," A., Vol. XCII., p. 608, 1915.

Dearle * to the importance of the wave length $\lambda=10140$ Å.U. in the spectrum of mercury. This wave length, which is just four times the wave length of $\lambda=2536{\cdot}72$ Å.U., is the first member of the series $\nu=(2{\cdot}5,\ S)-(m,\ P)$, and possesses the greatest amount of energy of all the wave lengths in the radiation emitted by the mercury arc. It has been shown by Dearle, moreover, to be readily absorbed by ordinary non-luminous mercury vapour even when the density of the latter is very low. Quite recently Dearle † has also shown that mercury vapour bombarded by electrons can be made to emit radiation of wave-length $\lambda=10140$ Å.U. when impact voltages as low as 5 volts are used. The quantum relation requires an impact voltage of 1·26 volts for the stimulation of this wave length, and it would be interesting to see if the vapour can be made to emit radiation of wave length $\lambda=10140$ by using an impact voltage of this amount.

The investigation is, however, one of great difficulty. In order to get over troubles arising from absorption, the vapour pressure of the mercury must be very low, and when vapours of low density are used the intensity of the radiation emitted is consequently feeble. With linear thermopiles of the most sensitive type and a Paschen galvanometer, such as Dearle used, it is difficult to make definite and satisfactory measurements when the radiation investigated becomes very feeble in intensity. As far as Dearle's experiments take us, however, they lend some support to the view that the quantum relation will give the requisite voltage for the stimulation from mercury vapour of an emission of the radiation $\lambda=10140$ Å.U., just as it has been found to apply to the stimulation of radiation consisting of single line, double line or many line spectra from the vapours of mercury, zinc, cadmium and magnesium under the experimental conditions already specified. If it should turn out to be true that mercury vapour in its ordinary condition can be made to emit the radiation $\lambda=10140$ Å.U., under bombardment by electrons possessing kinetic energy corresponding a P.D. of 1·26 volts, there is suggested the possibility of stimulating the vapour, by increasing the impact voltages, to the emission of radiation consisting of the wave lengths constituting the higher members of the series $\nu=(2{\cdot}5,\ S)-(m,\ P)$, of which $\lambda=10140$ Å.U. is the first

* McLennan and Dearle. "Phil. Mag.," Vol. XXX., p. 683, 1915.
† Dearle. Communicated to The Royal Society, Oct., 1918.

member. This, in turn, suggests the possibility of there being a new type of ionisation potential for mercury atoms corresponding to the frequency $\nu=(2\cdot5, S)$. On evaluating this ionisation potential by the quantum relation, it comes out as approximately 2·5 volts, which is just about one-quarter of the accepted value of the ordinary type of ionisation potential for mercury. What bearing Dearle's results may have on the views presented in this Paper is not as yet clear, but it is evident that they open up a line of attack for still further extending our knowledge of the origin of radiation, and possibly, too, of adding to what we know at present of atomic structure.

I.—*Low-voltage Arcs in Metallic Vapours.* *By Prof.* J. C. McLennan, *F.R.S.*

Received October 21, 1918.

I. Introduction.

In a Paper by Millikan* and in one by Hebb† experiments are described in which arcs were established in mercury vapour bombarded by electrons when the P.D.s applied were considerably less than those which the experiments of Bergen Davis and Goucher‡ have indicated are requisite to accomplish the ionisation of mercury atoms.

In particular Millikan and Hebb found that under certain specified experimental conditions it was possible to cause arcs to be struck in mercury vapour with applied P.D.s as low as 4·7 volts. Moreover, they also found that arcs so struck could be maintained in the vapour when the applied field was reduced to as low as 3·2 volts. Hebb also found that it was possible, under certain conditions, to cause the mercury vapour to radiate out light of wave length $\lambda=2536{\cdot}72$ Å.U., when the applied field in which the electrons were projected was as low as 2·5 volts. As these results would appear to be in conflict with what should be expected on the basis of the quantum theory, namely, that the ionisation potential is given by $V=\frac{(1{\cdot}5,\ S)h}{e}$, where $(1{\cdot}5,\ S)$ is the frequency of the shortest wave length in the principal singlet series $\nu=(1{\cdot}5,\ S)-(m,\ P)$, it was considered necessary that the experiments should be repeated and the results either confirmed or disproved.

With a view to doing this, some experiments were recently made for me by Mr. R. Harmer and Mr. F. W. Kemp in the Physical Laboratory at Toronto.

In these the vapours of cadmium and zinc, as well as that of mercury, were used, and the results obtained go to confirm the findings of Millikan and of Hebb. An account of the experiments follows.

* Millikan, "Phys. Rev.," Vol. IX., No. 5, p. 378, 1917.
† Hebb, "Phys. Rev.," Vol. IX., No. 5, p. 371, 1917.
‡ Bergen Davis and Goucher, "Phys. Rev.," Vol. X., No. 2, 1917.

II. Experiments by R. Harmer.

(*a*) *Discharge Tubes.*

In the course of these experiments it was found that the potentials necessary for producing arcs in mercury vapour varied capriciously and irregularly with changes in the temperature of the incandescent cathodes with changes in the density and temperature of the mercury and with changes in other factors not specially under control. It was decided to clear up these difficulties, if possible, and various modifications were made in the arrangement and form of the different parts of the discharge tube.

The form of tube which ultimately gave regular uniform and concordant results is that shown in Fig. 1.

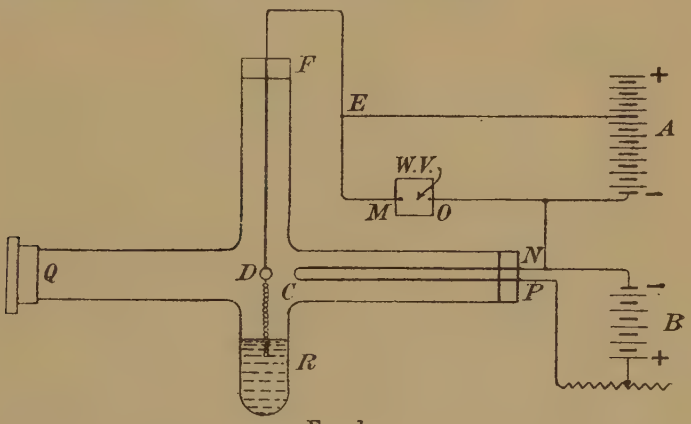

Fig. 1.

The tube itself was made of fused quartz. *C* was an incandescent cathode and *B* the heating battery. *PC* and *NC* were leading-in wires. *A* was the impact voltage battery. The positive terminal *EF* was an insulated iron wire terminated by an iron ring *D*, whose plane was at right angles to the axis of the discharge tube. A short chain with iron links kept the ring in electrical connection with the mercury in the reservoir of the discharge tube. This latter arrangement, it was found, contributed very definitely to obtaining regularity in the results. As shown in Fig. 1, *N* and *P* were respectively the negative and positive terminals of the heating battery. The negative terminal of the "impact voltage" battery was connected to *N*, and the positive terminal to *E*.

Readings on a standard Weston voltmeter W.V. joined up between *M* and *N*, gave values which were taken as the "impact voltage" between the ring *S* and the cathode *C*. With the arrangement shown it will be seen that these readings represented the maximum impact voltages present in the tube, including the potential fall in the incandescent cathode itself. The leading-in wires *E*, *F*, *NC* and *PC*, were stout, and had practically a negligible resistance.

(*b*) *Density and Temperature of the Mercury Vapour.*

With the incandescent cathode, whether simply a tungsten wire or a limed platinum strip kept with a definite and fixed heating current passing through it, it was found that as the density of the vapour increased, and possibly also the temperature, the applied voltages necessary to establish arcs gradually fell.

In one particular set of experiments in which a limed platinum strip cathode was used the reservoir *R* was about half filled with mercury. The cathode was then made incandescent, and the mercury was gently heated with the hot gases from a Bunsen burner placed near *R*. The potential required to produce an arc under these circumstances was 17·6 volts. The Bunsen burner was then placed so that its flame was directly in contact with *R*, and the mercury was made to boil. Under these circumstances the arcing potential fell to 10·2 volts.

The burner was then removed and the mercury allowed to cool. After about $1\frac{1}{2}$ minutes a series of arcing potentials was begun, and readings were taken at intervals. This series, which began at 14·2 volts, showed that as the mercury cooled the P.D. necessary to produce arcs gradually rose to as high as 23·8 volts. With the last-mentioned voltage the mercury in *R* was quite cool. The record of results is given in Table I.

These results, which are typical of many others which were obtained, show that the density of the vapour, and possibly also the temperature of it, had much to do with the lowering of the arcing potential. As the tungsten filament was intensely bright in the experiments III., and as the reservoir of mercury was some 6 cm. or 7 cm. below the filament, it is not considered that the heat from the flame affected to any appreciable extent the temperature of the filament. It should also be noted that no fluorescence of the mercury vapour was visually observed during the heating of the mercury.

TABLE I.

I. Platinum-limed Cathode.

State of mercury.	Arcing potential in volts.
Mercury warmed with hot gases	17·6
Mercury hotter	17·0
Flame in contact with reservoir	10·27
	10·26
	10·26
	10·26
Mercury left to cool for 1½ minutes	14·2
Mercury gradually cooling	14·9
	16·3
	17·0
	17·9
	18 8
	19·3
	19·6
	20·6
	21·4
	22·0
	22·6
Mercury quite cool to hard	23·8

II. Tungsten Filament.

Heating current.	Arc struck at
14 amperes	7·6 volts.
,,	9·4 ,,
,,	9·67 ,,
,,	9·92 ,,
,,	10·2 ,,
,,	10·44 ,,
,,	10·6 ,,
,,	10·64 ,,

REMARKS.—Mercury at first made very hot, and Bunsen burner was then removed, and mercury allowed to cool gradually.

III. Tungsten Filament Cathode Carrying 14·4 Amperes.

State of mercury.	Arcing potential in volts.
Mercury hot, flame low, no bubbling	8·8
Mercury hotter, flame higher, mercury still not bubbling	7·2
Mercury much hotter, and bubbling	6·2

(*c*) *Results.*

The series of results given in (*b*) shows that the arcing potentials which were obtained when a tungsten filament was used were much lower than those obtained with a platinum cathode. This result was invariably obtained. It may have been due to the fact that it was not found possible to heat the platinum to as high a temperature as the tungsten. This would probably result in the volume and average speed of the streams of electrons from the cathode being greater with the tungsten filaments than they were when the platinum strips

were used. In all the experiments, unless specially mentioned otherwise, tungsten wire 15 mils in diameter was used. In the case of platinum the cathode was made of a narrow strip of thin sheet metal.

(*d*) *Temperature of the Incandescent Cathode.*

In all the experiments it was found that whether the mercury vapour was dense or rare, the arcing potentials always decreased as the temperature of the cathode was raised. This again may have been due to a consequent increase in the volume and average speed of the streams of electrons ejected. The following examples serve to illustrate the point :—

TABLE II.

I. Tungsten Filament.

State of mercury.	Arcing potential in volts.	Heating current, amps.	Remarks.
Mercury quite hot and surface continually agitated	5·7	14·0	Filament very brilliant.
Ditto	5·4	13·9	Filament brilliant.
Ditto	5·2	13·2	Filament not quite so brilliant.
Ditto	6·15	12·25	Filament bright.
Ditto	6·6	11·1	Filament red.
Ditto	7·5	10·1	Filament still red.
Ditto	No arc even at 23·4 volts	8·5	Filament dull red.

II. Tungsten Filament.

State of mercury.	Arcing potential in volts.	Heating current. amps.	Remarks.
Mercury warm, but surface not agitated	10·8	14·0	Filament very bright and glowing.
Ditto	13·6	11·0	Filament incandescent.
Ditto	20·0	9·7	Filament bright.
Ditto	None at 24·0	9·2	Filament red.

III. Tungsten Filament.

State of mercury.	Arcing potential in volts.	Heating current, amps.	Remarks.
Mercury hot and surface agitated	6·2	14·4	Filament very bright.
Mercury very hot and surface extremely agitated.	5·5	17·2	Filament extremely bright.

(*e*) *Arcing Voltages and Potentials Requisite to Maintain Arcs.*

In all the experiments it was observed that the voltage required to make the arc strike was generally higher than the P.D. necessary to maintain the arc. The establishment of the arc for a given applied voltage was always immediately accompanied by a drop of greater or lesser magnitude in the potential between the two electrodes of the discharge tube. When this occurred it was possible to lower the potential between the electrodes still further without the arc being extinguished. In these regards the phenomena of the arc were exactly the same as those which are known to characterise electric discharge in gases at low pressures produced by applying a gradually increasing P.D. to the terminals of a discharge tube. The following are illustrations of this effect :—

TABLE III.

I. Tungsten Filament.

Mercury quite hot and agitated.

Heating current.	Arc struck at	Arc extinguished at
Amps.	Volts.	Volts.
14·0	5·7	3·64
13·9	5·4	3·4
13·2	5·2	3·4
12·25	6·15	3·7
11·1	6·6	5·0
10·1	7·5	7·2

II. Platinum Limed Cathode.

Heating current.	Arc struck at	Arc extinguished at	Remarks.
Amps.	Volts.	Volts.	
7·3	17·6	14·6	Mercury hot, but not agitated.
,,	10·26	9·0	Mercury very hot.
,,	14·2	13·8	Mercury cooling.
,,	17·9	17·5	,, ,,
,,	21·4	20·8	,, ,,
,,	22·0	21·5	,, ,,
,,	22·6	21·8	,, ,,
	23·8	22·6	,, ,,

III. Tungsten Filament.

Heating current.	Arc struck at	Arc extinguished at	Remarks.
Amps.	Volts.	Volts.	
9·3	11	9·0	Filament bright, mercury very hot.
9·1	18·1	17·1	Filament less bright, mercury cooler.
14·4	8·8	4·5	Mercury hot, no bubbling
14·4	7·2	4·2	Mercury hot, surface not agitated.
14·4	6·2	3·75	Mercury very hot and bubbling.
17·5	5·5	4·7	Mercury extremely hot.

IV. Tungsten Filament.

Heating current.	Arc struck at	Arc extinguished at	Remarks.
Amps.	Volts.	Volts.	Filament glowing.
14	7·6	6·5	Mercury strongly heated at first, and then allowed to cool slowly.
	9·4	8·7	
	9·67	9·35	
	9·92	9·74	
	10·2	9·94	
	10·44	10·28	
	10·6	10·4	
	10·64	10·45	

(*f*) *Minimum Arcing Potentials.*

From the results given above it is clear that the conditions which determined the establishment of the arc are somewhat complex. The general effect, however, of some of the main factors involved is evident. High temperature filaments and highly heated mercury were the factors which led to the lowest arcing voltages.

In a special experiment in which the cathode was a 10 mil tungsten wire heated almost to the melting point a series of results was obtained with the mercury strongly heated. These gave the lowest arcing potentials observed. In recording the readings sufficient time was allowed to elapse before taking each set in order to make certain that the vapour was under normal conditions. The readings are given in Table IV.

TABLE IV.

Arc struck at	Arc extinguished at
4·9 volts	3·4 volts.
4·96 „	3·25 „
4·75 „	2·86 „
4·95 „	2·84 „
5·0 „	2·87 „
5·01 „	3·25 „

From these results it will be seen that the lowest voltage at which it was found possible to strike the arc in mercury was 4·75 volts. The lowest P.D. which sufficed to maintain such an arc when once struck was 2·84 volts. These results are in good agreement with those obtained by Hebb, who found, as stated above, that under certain conditions arcs in mercury vapour could be struck with impact voltages of 4·7 volts, and maintained with applied P.D.s down to 3·2 volts.

It should be pointed out that in all the experiments described the distance between the edge of the positive ring electrode and the incandescent filament was about 1·5 cm.

Throughout the experiments small variations of 2 mm. or 3 mm. in this distance did not appear to change the arcing voltages. It would have been interesting to see if variations in the electrode distance of a somewhat greater amount produced any effect on the results. This point, however, was not specifically examined.

III. EXPERIMENTS BY F. W. KEMP.

I. *Arcing Potentials in Zinc and Cadmium Vapours.*

(*a*) *General Conditions.*

In the first of these experiments the conditions governing the establishment of arcs in zinc and in cadmium vapour were studied. The form of discharge tube used is shown in Fig. 2, and was the same as that used by McLennan and Henderson.* The streams of bombarding electrons were of moderate intensity. Three quartz tubes were fused to a central receptacle *C* to form a T. At *A* and *E* the electrodes *B* and *D* were introduced through ebonite plugs, sealed in the ends of the tube with wax. At the end of the third branch a ground joint *G* was fitted with a glass tube. Into the glass tube were sealed two stout low-resistance wires, *H* and *K*, leading to the filament *F*. *F*, *B* and *D* each just reached to the edge of

* McLennan and Henderson, "Proc." Roy. Soc., A., Vol. XCI., p. 485.

the receptacle C, in which was placed the metal to be studied. Through the ebonite plug at E a tube was connected to an air pump. During all the experiments the apparatus was kept highly exhausted. K and D were externally connected, thus F and D constituted a double cathode with B as the anode. B and D were made from rods of the metal whose vapour was being studied. The filament F was heated by an alternating current, and the metal in C was melted with a gas burner. A direct current P.D. was applied between B and D.

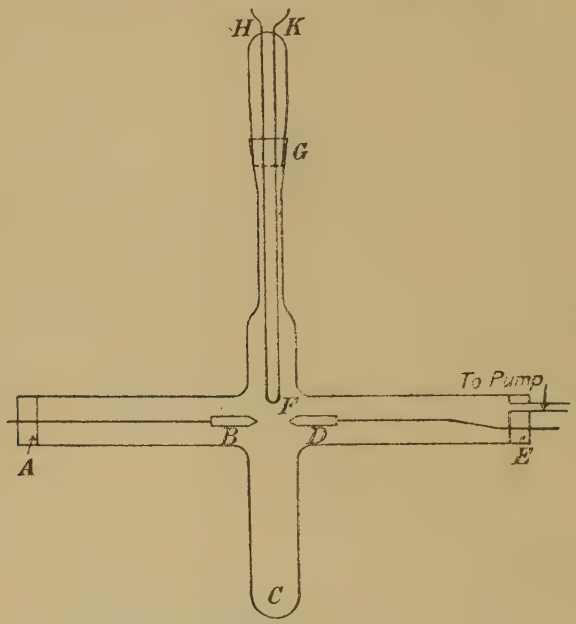

Fig. 2.

With the filament, which was a 10 mil tungsten wire at a bright red or white heat and the metal boiling, it was found that the arc in both zinc and cadmium vapours would strike at between 10 and 12 volts. It would persist to a lower voltage, though with certain densities the striking and breaking voltages were more nearly equal than with others. With the vapour either very dense or very rare the difference was large. The least difference seemed to come with densities corresponding to a temperature slightly below the boiling point of the metal. This density also gave the lowest values for the

arcing potential. If the flame were removed from the receptacle *C* the arcing potential lowered a little as the metal cooled and then went up quite rapidly.

Also, as the supply of metal in the receptacle became low, the arcing potential went up. Below are some values taken consecutively just as the last few drops of molten metal boiled away :

TABLE V.

Zinc.			Cadmium.		
Current in filament.		Arcing potential	Current in filament.		Arcing potential.
Amps.	Volts.	Volts.	Amps.	Volts.	Volts.
9·1	3·0	10·7	9·25	3·3	10·3
		16·0	9·1	3·3	10·8
		16·8			11·0

It could not be stated definitely whether this rise was due to a variation in the temperature or in the density of the vapour, as the form of apparatus did not lend itself to the separation of these factors. It was probably, however, a density effect.

In both zinc and cadmium vapours two types of arc were observed. At a certain applied voltage the arc spectrum could just be seen in the spectroscope. By increasing the voltage it became brighter, but when a certain voltage was reached there was a very abrupt increase in brilliance, though no new lines were observed. This brilliant arc was never observed except with very dense vapour. With zinc this jump in brilliance occurred at a potential 0·7 to 1 volt higher than the lowest applied voltage at which the arc could be seen. With cadmium the difference was 0·5 to 1·2 volts. If the vapour were not so dense the brilliant arc could not be produced with 25 volts.

(*b*) *Effect of Rise in Temperature of Cathode.*

The temperature of the tungsten wire cathode was a large factor in altering the magnitude of the arcing potential. It this wire were not white hot no brilliant arc was obtained. The minimum arcing potential decreased as heavier currents were passed through the filament. This variation could be observed more closely than that due to vapour density or temperature. The two accompanying curves, Figs. 3 and 4, illustrate the effect of changing the temperature of the hot

cathode. The minimum arcing potential was plotted against the current through the filament cathode, which may be taken to represent approximately the temperature of the latter. The values plotted in Figs. 3 and 4 are given in Table VI.

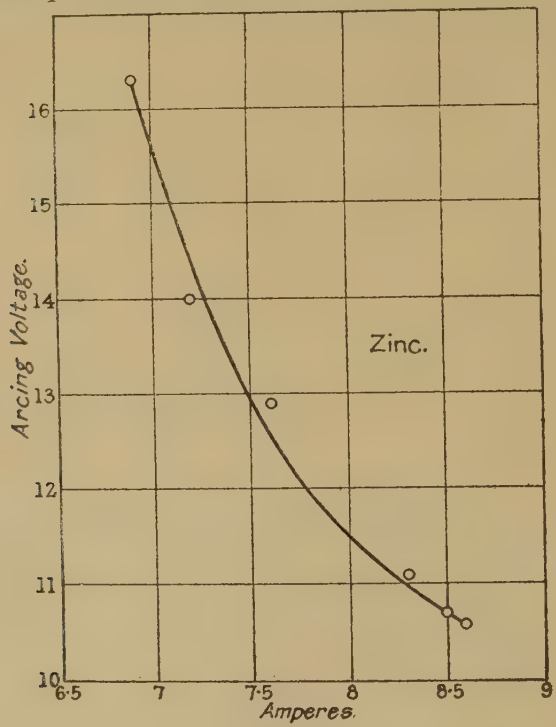

FIG. 3.

TABLE VI.

Zinc.		Cadmium.	
Current through filament.	Minimum arcing potential.	Current through filament.	Minimum arcing potential.
Amps.	Volts.	Amps.	Volts.
6·75	16·3	7·15	15·9
7·1	14·0	7·4	14·2
7·6	12·9	7·65	13·1
8·25	11·1	8·0	12·1
8·5	10·7	7·9	11·6
8·6	10·6	8·2	11·3
		8·15	11·2
		8·6	10·7
		8·6	10·4

The effect of variation in the temperature of the filament was shown in another way. A certain potential was applied which was not sufficient to bring on the arc. The temperature of the

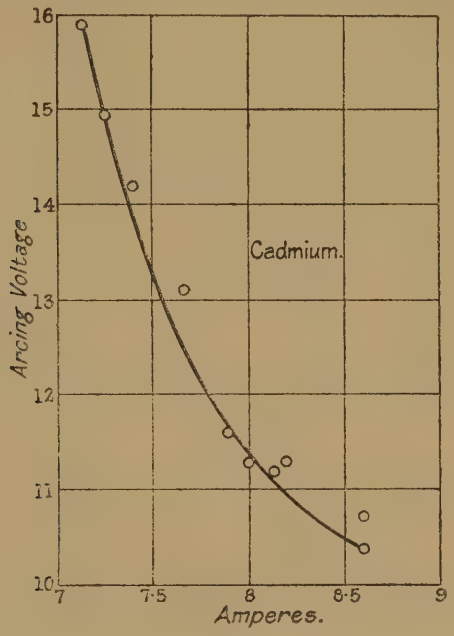

FIG. 4.

cathode was then raised, and the heating current noted as the arc became visible. This, however, lacked the precision that accompanied the former method, but as illustrative of the phenomenon the results are given :—

TABLE VII.

Zinc.		Cadmium.	
Fixed applied impact voltage.	Minimum current in filament when arc struck.	Fixed applied impact voltage.	Min. current in filament when arc struck.
Volts.	Amps.	Volts.	Amps.
10·2	9·3	10·1	8·5
10·3	9·3	10·4	8·25
11·1	9·1	10·6	7·95
10·4	8·2	11·6	7·9
11·2	7·6	12·0	7·8

As seen from Table VII., the minimum arcing potential was different under different conditions. There were, however, values below which with this type of apparatus the arcs would not strike. These values approximated very closely to the values calculated from the quantum hypothesis, though experiments to be described later will show that these were not the lowest values of the arcing potentials obtainable. The table of values (Table VIII.) were the minima of several sets of readings. The size of the wire used for the hot cathode was the same for each, but not the length. There was also a slight variation in vapour density and distance between electrodes for the different values.

TABLE VIII.—*Minimum Arcing Potentials.*
First Set.

Zinc.		Cadmium.	
Calculated from $V=\frac{h(1\cdot5,\ S)}{e}$	Experiment.	Calculated from $V=\frac{h(1\cdot5,\ S)}{e}$	Experiment.
Volts.	Volts.	Volts.	Volts.
9·24	10·49	8·85	10·3
	10·0		10·1
	9·7		10·06
	9·5		9·6
	9·4		9·3

In obtaining these values a standard voltmeter gave the P.D.s between B and D, and a second one the P.D.s between H and K. As the heating current was an alternating one the values given in Table VIII. were obtained by adding the direct current potential fall between F and B to the maximum value of the P.D. in the alternating-current cycle between H and K.

The results of these experiments, it will be seen, are in practical agreement with the results of the original experiments of McLennan and Henderson,* where it was found that the impact voltages which brought on the arc and consequently the many lined spectrum, were given by the quantum relation $Ve=h\nu$, ν being the frequency of the shortest wave length of the series of wave lengths given by $\nu=(1\cdot5,\ S)-(m,\ P)$. Two points of special importance which were brought out in these experiments are (1) that the minimum arcing potential corresponded to a definite density of the vapour bombarded, and (2) that there were two types of arc

* McLennan and Henderson, loc. cit.

obtainable in vapours of considerable density. With both types the many lined spectrum of the metal vaporised was obtained, but the two types differed markedly in brilliancy, and it was possible to pass from the faint type to the brilliant type by a small addition to the impact voltage applied. A point which should be noted in regard to this matter is that with the brilliant type of arc there was always present and superimposed upon the line spectrum a strong continuous white light spectrum. With the faint type of arc, while the line spectrum stood out clearly, there was a total absence of anything like a continuous white light spectrum in the background.

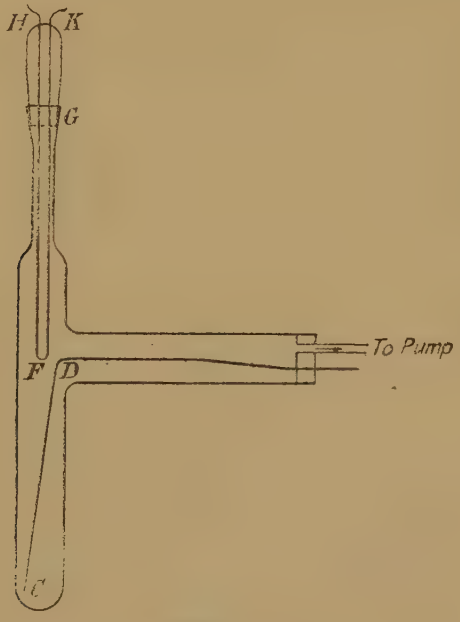

FIG. 5.

II. *Arcing Potentials in Mercury Vapour.*

(*a*) *General Conditions.*

Some experiments were also carried out with mercury vapour. For these the tube shown in Fig. 5 was used. In some of the experiments tungsten wire 10 mil in diameter was used for the hot cathode, and in others platinum foil carrying a spot of calcium oxide was used. The tube, Fig. 5, differed from that in Fig. 2, in that there was a single cathode, namely, the hot filament *F*. *D*, the anode, was made of steel

wire dipping down into the receptacle C, which contained the metal to be vaporised. The tube was made of fused quartz, and the metal in C was vaporised by the heat trom a Bunsen burner.

Mercury.

The arcing potential for mercury vapour was found to depend upon the temperature of the cathode, much as was the case with zinc and cadmium. The mercury was always kept boiling, and the potential at which the arc broke was lower by $\frac{1}{2}$ volt than the striking potential. In this regard, too, mercury vapour behaved similarly to the vapours of cadmium and zinc.

With the tungsten wire kept intensely hot and the mercury boiling the arc was obtained with impact voltages as low as 6 volts. With platinum foil bearing a spot of calcium oxide and heated to a white heat a P.D. as low as 8 volts established the arc. The platinum foil would not stand the same high temperature as the tungsten filament, and the difference in the arcing voltage was probably due to a cause associated with this condition.

(*b*) *Experiments with Hot Cathodes and Anodes.*

In a special set of experiments a tube was arranged with the electrodes similar to the negative electrode in Fig. 5. Each electrode had its own heating circuit, and the impact voltages were applied by means of a battery inserted between the circuits of the two electrodes. In these experiments the arc in mercury vapour was never obtained with less than 12 volts. The temperature of the anode had little effect, if any, and, as the values given below indicate, the heating of the anode did not in any way produce a lowering of the arcing potential. The following are the results obtained in one set of observations:—

TABLE IX.

Heating currents.		Arcing potential.
Cathode.	Anode.	
Amps.	Amps.	Volts.
6·2	4·7	12·0
6·2	5·7	12·3
6·2	7·4	13·6

The form of apparatus used in these experiments helped to bring out the effect of variations in vapour density and

temperature. With the mercury boiling the minimum arcing potential was found. Then the flame was removed, and as the apparatus cooled the minimum value diminished for a short time, but as further cooling took place it rose rapidly. Table X. illustrates this effect, V_1 representing the potential required, while the metal was boiling, and V_2 the arcing potential at the turning point as the vapour cooled.

TABLE X.

Heating currents.		Arcing potential.	
Cathode.	Anode.	V_1.	V_2.
Amps.	Amps.	Volts.	Volts.
5·8	4·7	18	14
6·2	4·7	14	12
6·2	5·7	13	12

III. *Low-voltage Arcs in Cadmium Vapour.*

In working with the cadmium vapour a third set of experiments was made with a tube of the form shown in Fig. 6.

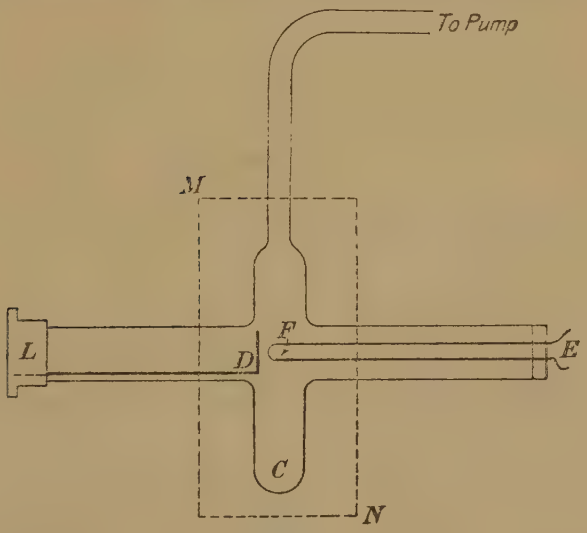

FIG. 6.

This tube had three branches of fused quartz, one of which was used only to connect it to the pump. The cathode F was a 15 mil tungsten wire, the leads entering through the ebonite plug at E. The anode D was a heavy iron wire

ring, whose centre was in line with the cathode, and whose edge was everywhere not more than 4 mm. from the latter. Over the end of the tube there was waxed an iron sleeve, L, carrying a glass window, and the wire leading to the anode was soldered into this sleeve. The receptacle C and the neighbouring parts were heated by an electric furnace, $M\ N$, and the temperature of the metallic vapour in C was calculated from the temperature coefficient of resistance of the wire composing the furnace. The filament F was heated by a direct current, the negative end of which was connected to earth. The arcing potential was ascertained by measuring the P.D. between D and the earthed lead of the filament.

With the use of an electric furnace it was possible to maintain the vapour in the discharge tube much more definitely at any selected temperature than it was with the use of a Bunsen burner. In the present instance the furnace was always maintained at a temperature of 400°C.

With the apparatus in this form the arc was found to have all the characteristics previously described. The difference in the voltage required to cause the arc to strike and that required to maintain it was quite pronounced. It was also found that it was possible to cause arcs to strike with voltages considerably below those demanded by the quantum theory on the basis of the ionisation potential being given by $V=\frac{h\times(1\cdot5,\ S)}{e}$, $(1\cdot5,\ S)$ being the frequency of the shortest wave length of the series $\nu=(1\cdot5,\ S)-(m,\ P)$.

The results given in Table XI. will serve to make these points clear.

TABLE XI.—*Arcs in Cadmium Vapour.*

The arc struck at	P.D. between electrodes dropped to	The arc broke at	P.D. between electrodes rose to
Volts.	Volts.	Volts.	Volts.
7·2	4·2	3·2	4·4
6·9	4·0	3·1	3·9
6·6	3·7	2·8	2·8
6·4	3·4	3·1	3·8

From the numbers given in this Table it will be seen that when arcs were struck with a given applied voltage the current in the arcs caused a drop in the actual P.D. between the electrodes. Moreover, when arcs were once established, it was necessary, as the numbers show, to reduce the voltage

applied externally in order to extinguish them. The drop in voltage between the electrodes just before the arcs were extinguished, it will be seen, was a little below the actual drop between the electrodes just after extinction had taken place.

As the ionising potential for cadmium given by the quantum theory is 8·85 volts, it will be seen that for cadmium vapour as for mercury vapour it is possible under certain conditions of cathode temperature and vapour pressure to establish arcs with applied P.D.s considerably below the value of the ionisation potential.

With the cathode at an intensely high temperature the arc would strike easily between 6 and 7 volts. In one particular case the applied P.D. was set at 5·5 volts, and the arc struck in 5 seconds. When set at 5·0 volts the arc struck after 2 minutes waiting. In this case when the applied potential was lowered the arc still persisted at 2 volts. At this low voltage the difference in potential between the positive end of the cathode filament and the anode was only of the order of 0·1 volt. When the applied P.D. was set slightly lower than 5 volts no arc appeared even with a 10-minute wait. In all the experiments the arc was never observed when the applied P.D. was lower than 2 volts. These low readings were taken when the cathode was extremely hot, and only a few readings could be taken before the filament had to be renewed through fusing.

Summary of Results of the Experiments by Harmer and Kemp.

1. It has been shown that increasing the temperature of the incandescent cathode lowers the voltage necessary to produce arcs in the vapours of mercury, zinc and cadmium.

2. With limed platinum cathodes arcing voltages were not obtained as low as with incandescent tungsten filaments.

3. With highly heated incandescent cathodes it was found that with vapour of low density the arcing potentials were generally high. When the density of the vapour was gradually increased the arcing potential fell and reached a minimum value at a certain density of the vapour. When the density of the vapour was still further increased the values of the arcing potentials rose again.

4. The voltages necessary to maintain the arcs in the vapours were found to be less than those which had to be applied in order to strike the arcs.

5. With mercury it was found possible to strike arcs with arcing potentials as low as 4·75 volts, and to maintain them an applied P.D. of 2·84 volts sufficed.

6. With cadmium vapour arcs were struck with impact voltages of 5 volts, and maintained with P.D.s of 2 volts. To obtain these low arcing voltages it was necessary to use intensely hot cathodes and a copious supply of highly heated metallic vapour.

In many of the experiments it was noticed that when certain voltages near the minimum ones were applied no arc appeared in the vapour forthwith, but arcs did finally strike when an interval of time of greater or shorter length was allowed to elapse.

7. With moderately heated incandescent cathodes and a moderate supply of metallic vapour the arcing voltages with mercury, zinc and cadmium vapours under electric bombardment were given by the quantum relation $V=\frac{h\times(1\cdot5,\ S)}{e}$, where $(1\cdot5,\ S)$ is the frequency of the shortest wave length in the $\nu=(1\cdot5,\ S)-(m,\ P)$ series.

8. In experiments with cadmium vapour it was found to be possible to set up two types of arc in the vapour, the one being faint and the other brilliant. The line spectrum of the two types appeared to be the same in character, but different in intensity. Additions of a P.D. in the applied field of not more than a volt generally sufficed to enable one to pass from the faint to the brilliant type. With the brilliant arcs a continuous white light spectrum was superimposed upon the line spectrum.

9. Irregularities in the experimental results were in a measure removed when the metal being vaporised was electrically connected to the positive terminal of the discharge tube.

The Physical Laboratory, University of Toronto,
July 1, 1917.

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